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U.S. DEPARTMENT OF TRANSPORTATION
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NUCLEAR WASTES IN COMPARISON WITH OTHER HEAT SOURCES FOR DEICING OF BRIDGES, RAMPS, AND PAVEMENTS

Final Report

Phase I

September 14, 1970

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Dynatherm Corporation
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Cockeysville, Maryland

U.S. DEPARTMENT OF TRANSPORTATION

FEDERAL HIGHWAY ADMINISTRATION

SUBJECT		
SUBJECT	Nuclear Wastes in Comparison With Other Heat Sources for Deicing of Bridges Ramps and Pavements	FHWA NOTICE

July 19, 1972

HRS-41

The attached report was developed by the Dynatherm Corporation and summarizes the results of Phase I of the subject research study. This study (1) investigated the performance and cost-effectiveness of varied nonchemical bridge and roadway deicing systems installed throughout the United States and (2) compared these existing systems with the predicted performance and cost of a system using the decay heat of fission products and a system using the stored heat of the earth itself.

Report Summary

The report concluded that: (1) None of the existing systems for nonchemical deicing can be considered general solutions to the problem for a variety of reasons. (2) The system using the natural heat of the earth seems to have the lowest annual operating cost. (3) A system using fission products has many technical problems inherent in any project using potentially dangerous fission products. (4) The system selected for further detailed design and study is one using the natural earth as a heat source.

Application of Findings

This report could be of value in deciding what type of non-chemical deicing system to install in any problem area a State might have where such a system could be justified.

Charles F. Scheffey

Charles F. Scheffey
Director, Office of Research

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NUCLEAR WASTES IN COMPARISON WITH OTHER HEAT SOURCES FOR DEICING OF BRIDGES, RAMPS, AND PAVEMENTS

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ABSTRACT

Over the past 20 years, a number of non-chemical roadway and bridge deicing systems have been installed in various parts of the United States. Various forms of heating have been incorporated in these systems and include steam from power plants, electricity, fossile fuels and hot water from natural springs. The reported performance and cost experience of these systems was studied and compared with the predicted performance and cost of a nuclear system using the decay heat of fission products and that of a system using the stored heat in the earth itself.

Experience has shown that delicate in-pavement heating elements are subject to early failure. Good engineering practice dictated that, in order to obtain a high system reliability for severe operating environments, sufficient redundancy had to be provided to permit random failures to occur without impairing system performance. Furthermore, the ecological implications of the systems evaluated were considered.

Based upon these considerations and those of cost, a highway heating system using natural earth heat was selected for further study. This system will be augmented by nuclear fission product heat or by solar/ambient heat for special locations where natural earth heat is insufficient to supply the required energy.

[illegible]

I. PROBLEM DEFINITION

A. Introduction

In spite of current public resistance which seeks to slow down the development of nuclear power because of environmental issues, the fact remains that, on balance, nuclear power is far less destructive of the natural environment than fossile fuel plants. When this becomes generally recognized by the public, the emphasis will shift towards nuclear power and the estimates used in this study for determining the availability of nuclear waste are quite likely to be conservative.

Fission products (nuclear wastes) are a by-product of fuel reprocessing plants and must be disposed of in a safe and acceptable manner. This is a major problem to the nuclear industry. Currently, the West Valley, New York, facility is storing the waste as a liquid in double walled tanks. These tanks must be abandoned every ten years for safety considerations, and the waste must be stored in new tanks. Alternately, the General Electric Company, at its new Morris, Illinois, reprocessing plant, plans to encapsulate the waste (after a 5-year cooling down period) and store these encapsulated wastes in abondoned salt mines.

The concentration and encapsulation of wastes after an initial holding period appears to be a practical solution to the long-term storage problem. The long-term solution to the disposal problem is still under evaluation. This study considers the long-term storage of wastes at critical highway interchanges and the utilization of the decay heat for roadway deicing. Basic assumptions used in this study are:

1. The fuel reprocessing facility will supply concentrated, encapsulated nuclear waste to the designated highway site at no cost.

2. Responsibility at the site will be transferred to the highway system. This responsibility will include the safe and acceptable storage of the waste and the responsibility of ultimate disposal should this become necessary.

The heat generated by nuclear waste cannot be controlled. This heat must be dissipated continuously in order to avoid excessive temperatures in the nuclear waste. In order to utilize this heat effectively for highway deicing, heat generated during the summer and during times of no demand must be stored. The identification of an effective and economical storage method is an important part of this study.

B. Interchanges

Interchanges vary in size and configuration from location to location. It is impractical for a comparative study between various deicing systems to design, even in conceptual form, individual systems for individual interchanges. A typical interchange was therefore selected. For this interchange--the steel beam bridge over Baltimore County beltway--a complete set of plans including test borings were obtained from the State Road Commission, State of Maryland. The location was conveniently situated to permit periodic inspections and measurements. This installation has an access ramp area of approximately 67,200 ft^2, which appears to be average.

C. Selection of Heat Flux and Energy Requirements

The specified design of a highway deicing system depends not only on the size and nature of the interchange but also on the nature of the winter climate and the system design. The power demand depends upon:

1. Wind Velocity

2. Temperature

3. Rate of Snowfall

4. Type of Operation--i.e., continuous heating or intermittent heating

5. Operating Temperature of the Pavement Heating Elements

The annual energy requirement depends upon:

1. Annual Degree Days Below 32°F

2. Type of Operation--i.e., continuous or intermittent

3. Operating Temperature of the Pavement Heating Elements

4. Average Winter Wind Velocity

5. Number of Annual Snow or Icing Days

In order to define the climatic variables two representative locations were chosen. Baltimore was chosen to represent a moderate climate location; and this turns out to be fairly representative for the major East Coast cities such as Washington, Philadelphia, New York, and Boston. Binghamton, New York, was chosen to represent a severe climate--one which would be representative of inland eastern cities.

Finally, for the purpose of making a system comparative study, it was assumed that the power demand would be limited such that, during 90% of the time, complete and immediate snow removal would be accomplished. During the remaining 10% of the time, where, for example, the snowfall was 3 inches per hour and the wind velocity was 40 mph with a 0°F ambient, snow melting would occur at the rate of 1" per hour. Note that, even for this extreme case, the roadway surface beneath the snow cover would remain free of ice and removal of the cover by conventional means without the use of salt would be easy. In any event, given sufficient time, the system would eventually melt the snow cover under this severe environment.

D. Future Availability of Nuclear Waste Heat

Estimates of future nuclear power generation in the United States vary and are modified periodically. Figure I-1 presents the most current estimates. The AEC CONF-660208, February 1966, data was used in this study. The nuclear waste generated as a result of this power production is presented in Figure I-2. This data indicates that by 1995 approximately 800 thermal megawatts of waste heat would be available, the latest of which would have been discharged from the reactors in 1994. For purposes of simplicity of system design and using data made available by the General Electric Company, a five-year decay period was permitted before the encapsulated fuel was made available to the highway system. This additional decay period reduces the nuclear waste heat made available for highway heating by about a factor of 8.

Although, as indicated previously, these estimates will probably prove conservative, the fact remains that the available nuclear waste heat is limited when expressed in terms of total demand for highway heating systems. This study, therefore, directs attention to utilizing this limited heat availability most effectively. For example, by designing a storage system with a conservatively estimated efficiency of 50% the number of installations to be served can be increased by a factor of 6. Furthermore, by using the earth as a natural storage system and recognizing that the earth has a tremendous amount of natural energy, waste heat may be used to augment this heat in special situations. A 10% augmentation would permit the number of installations to be served to increase by a factor of 10. Using earth heat and earth storage, it is conceivable that the total number of installations that can be served with the available waste heat can be increased by a factor of 50.

FIGURE I-1: PREDICTED TOTAL U.S. NUCLEAR POWER

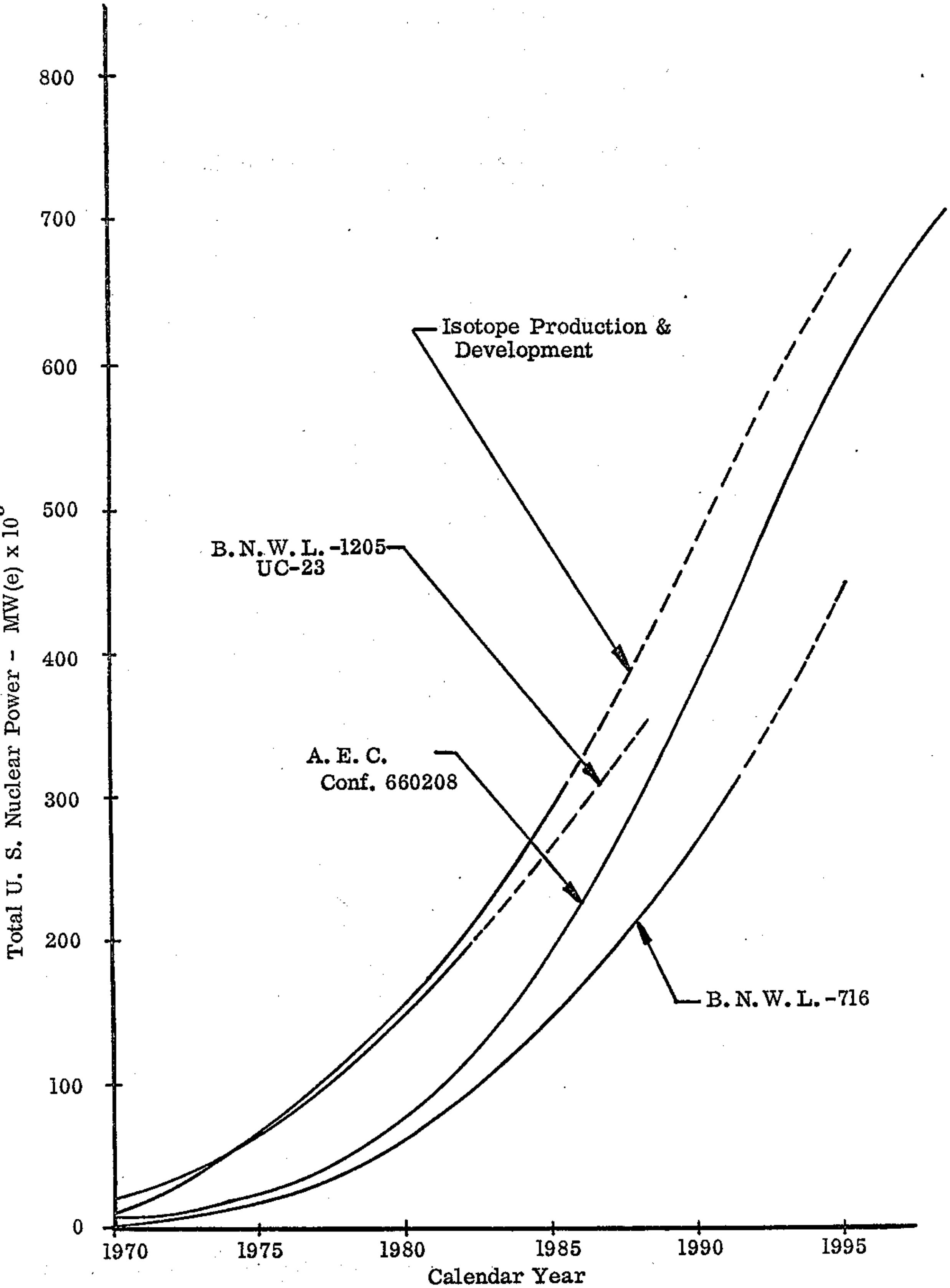
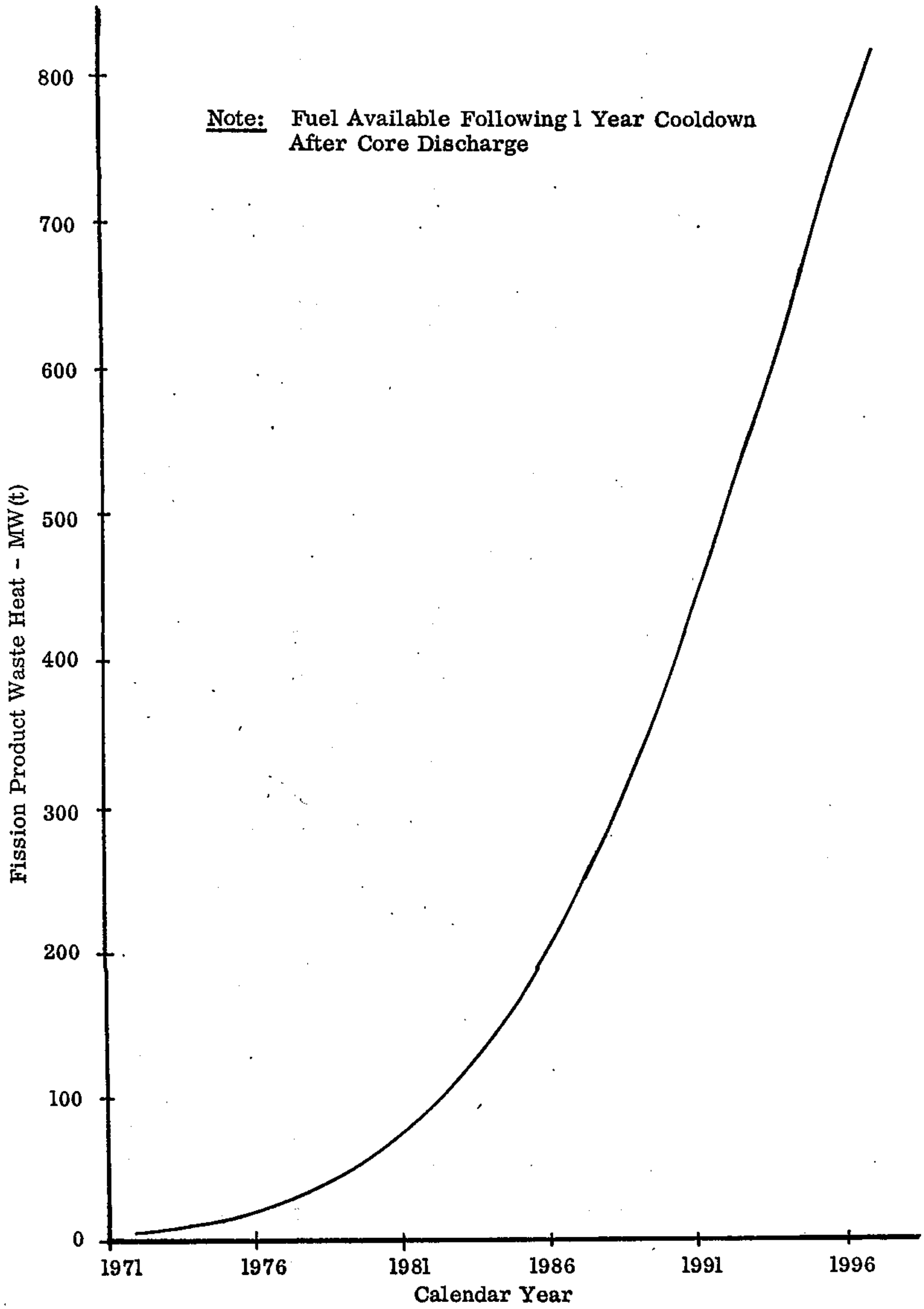


FIGURE I-2: CUMULATIVE FISSION PRODUCT WASTE HEAT AS A FUNCTION OF CALENDAR YEAR



II. FUNCTIONAL SYSTEM SPECIFICATIONS

The following list of functional specifications was used to guide the system designer during this conceptual phase:

A. Safety

The system shall improve the safety and dependability of highway travel. Once the system is implemented the motorist will learn to depend on it. Unless the system can be demonstrated to have a high degree of reliability, the motorist must be protected against the hazards introduced by system failure. This protection may be in the form of visual warning signs which light up when a system failure has occurred.

The system "of itself" must be safe. This applies particularly to the nuclear system where the primary danger to be protected against is the release of fission products to the earth and/or ambient environments.

B. Reliability

The system shall be designed so that the failure of any one element shall not make the entire system inoperative. Ideally, the system should be redundant, simple and inherently reliable.

C. Ease of Installation

The system should be easy to install, preferably, with personnel and equipment common to current highway construction practice.

D. Economy

The operating and installation costs of the system should be as low as possible consistent with the requirements of safety, reliability, and installation requirements. The system should require no maintenance or, at the most, it should be simple to maintain. The costs of the system must be justified by the properly assessed costs of improved highway safety, reduced highway maintenance, increased reliability of the transportation system to the motorists, and any reduced maintenance costs accrued to the motorist.

The direct operating costs of the system are determined by the cost of energy and by the cost of labor and materials required to maintain the system. The costs associated with maintenance must be determined by actual experience, although general estimates can be determined by system complexity, costs of subelements of the system, and the ease of replacing parts and components.

The indirect operating costs of the system are determined by system useable life. A system with a useable lifetime of five years would incur an additional yearly operating cost of at least one-fifth of the installation cost. This assumes that the entire system requires replacement on one hand but does not consider removing the old pavement prior to installing a new system should this be required.

III. SUMMARY OF RESULTS OF STUDY

A. Summary Chart

Results of the Phase I comparative study are summarized in Tables III-1 and III-2. Data (Table III-1) for systems 1 through 7 were obtained from literature. For these systems, average costs were used when several varying costs were reported. No attempt was made to consider increased current material and labor costs for those systems constructed years ago.* Also, the systems were not normalized for one climatic condition. The reported values for systems 8, 9, and 10 (Table III-2) are based on cost analyses of conceptual designs for a selected interchange and a selected ambient environment.

Estimated system useful life is based on reported experience for those systems which have been constructed and tested. For systems 8, 9, and 10 the guideline for reliability (see functional requirement II-b) was used in the conceptual design. Life of these systems was estimated considering experience on related system elements and upon the ability of these systems to tolerate random failures without impairing system function.

The data for systems 8, 9, and 10 are an average for systems designed for a moderate climate (Baltimore) and those designed for a severe climate (Binghamton). The ability of the earth to recover its heat during the summer months for the Binghamton climate (system 8) may be marginal, and some form of augmentation such as nuclear or solar/ambient may be required. For system 9 the entire annual energy requirement was assumed to come from nuclear waste, whereas a significant portion can actually come from the stored heat in the earth.

The cost data are presented in terms of both operating and capital costs.

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*As reported by the Federal Highway Administration, the Highway Construction Price Index has increased $42\frac{1}{2}\%$ since 1958.

TABLE III-1

SUMMARY OF HIGHWAY HEATING SYSTEMS
(REPORTED DATA)

		Average Operating Cost ¢/Ft^2/Yr	Average Install. Cost ¢/Ft^2	Estimated Lifetime Years	Cost ¢/Ft^2/Yr	
1.	Mechanical/Chemical (1969)	0.6	--	--	--	Costs reported for all road surfaces
2.	Bare Wire - Electrical (1952)	3.5	225	2	115	Subject to wire breakage
3.	Shielded Wire - Electrical (1958)	9	400	5	89	More reliable than bare wire
4.	Conductive Surface (1968)	3.5	100	1	104	Questionable for general traffic
5.	Oil Burners (1957)	2	400	3	132	Hot water or fluid systems unreliable
6.	Infrared (1969)	35	1000	10	135	Inefficient
7.	Commercial Steam (1954)	12.5	350	--	--	Limited Availability

TABLE III-2

SUMMARY OF HIGHWAY HEATING SYSTEMS
(CALCULATED DATA)

		Average Operating Cost ¢/Ft^2/Yr	Average Install. Cost ¢/Ft^2	Estimated Lifetime Years	Cost ¢/Ft^2/Yr	
8.	Natural Earth	0	450	15	30	Must be augmented for severe climates
9.	Nuclear - Earth Storage	0	700	15	47	Limited Fuel Supply
10.	Electrical - Heat Pipe Mat.	14.5	600	10	75	Operating Costs based on commercial rates

Absolute yearly costs are calculated by dividing the capital costs by the estimated lifetime and adding the annual operating costs. No allowances are provided for the cost of money. (Calculations indicate that this refinement does not materially effect the relative costs and may be subject to questionable assumptions.)

Some inconsistencies in the cost data are evident. For electrical systems 2, 3, and 4 the reported operating costs are significantly lower than that calculated for system 10. The operating cost for mechanical/chemical snow removal methods is based on average report costs for all roadway surfaces for Maryland and Vermont. Costs for interchange snow and ice removal would be considerably higher and are estimated to be 20 cents per square foot per year for a capability comparable to an automatic system.

B. Conclusions

Although several roadway heating systems have been constructed during the last 15 years, none can be considered general solutions for a variety of reasons. The major reasons are:

1. Poor reliability
2. High costs
3. Restrictive heat sources; i.e., natural hot water springs, commercial steam

A few systems failed because of poor or improper design. Applying more restrictive construction practices, improving individual component reliability, and correcting poor design practices may improve these systems; but it is doubtful whether it will change this conclusion.

The system and system combination which is the most attractive in terms of cost, reliability and general applicability is system 8 augmented, where required, by nuclear or by a natural heat source such as solar or the environment. Although this system has not been constructed, snow removal using the natural heat of the earth has been demonstrated (Reference III-1). The design and the problems associated with application of this design to the selected typical interchange have been investigated. It must be recognized that specific interchanges, bridges, and highway pavements may represent new problems for any system and, as such, may require some component redesign for the intended application. A brief study of special cases was made, and it appears that the selected system is flexible enough to handle most problems without major design changes.

C. System Selection and Recommendations

The system selected for further detailed design and for application to highway deicing and snow removal is defined as follows:

1. The heat source and storage is natural earth.
2. The heat transport is by heat pipes suitably arranged to make the required volume of earth available to the roadway surface.
3. The heat distribution in the pavement is by heat pipe mats which also act as reinforcement mats.
4. The heat control is by a simple temperature sensing valve which maintains the roadway surface above 32°F at all times.
5. Augmentation of earth heat required for severe climates and special situations is by:
   a. nuclear wastes heat
   b. solar energy
   c. ambient energy
   d. a combination of any two or all of a, b, and c.

The technologies of earth heat exchangers, heat pipes and highway heating for purposes of deicing and snow removal are relatively new. The techniques for handling fission products are established for controlled, in-plant processes. Techniques for safe handling and storage of the large quantities of relatively low specific activity nuclear waste for highway deicing and snow removal remain to be established.

During the conceptual phase of this study, certain assumptions were required which were based upon available data and theoretical calculations and are thought to be conservative. It is quite possible that the sum total of all assumptions results in a design which is overly conservative. During Phase II detailed design, further refinement of these assumptions will result; however, good engineering practice dictates that certain experimental and associated analytical work be accomplished prior to establishing the final construction plans for a specific installation. The following experimental/analytical work is recommended:

1. Construct a concrete slab of suitable size and suitably located which incorporates a heat pipe mat and cal-rod heaters which can be individually controlled. Measure temperature, wind velocity, snow and rainfall. Conduct natural and artificial icing experiments under appropriate conditions, and measure power and energy demands as a function of heater spacing. Correlate power and energy requirements to ambient conditions.

2. Construct a concrete slab of suitable size and suitably located which incorporates a heat pipe mat and heat pipe earth heat exchanger. Obtain measurements, as in (1) above, and visually and by measurement determine system deicing and snow removal performance. This

slab can be constructed in close proximity to the electrically heated slab (1) above.

3. Having determined experimentally and analytically the heat pipe and heat pipe mat configuration suitable for deicing and snow removal, simulate this design on the Department of Transportation Traffic Simulator or an equal in order to obtain accelerated life test data.

4. Evaluate the several most promising temperature sensing valves which may be inserted internal to the heat pipe, choose the most promising, construct it and performance test it.

5. Evaluate the several most promising systems for pumping summer heat down into the earth reservoir, choose the most promising, construct it and performance test it.

Note that several additional investigative efforts are identified in this report. Improvements in concrete cover conductivity will benefit any low temperature deicing and snow removal system. Although a number of investigators have made measurements of concrete thermal conductivity as a function of composition, moisture, density, etc., no work has been done to investigate methods by which the conductivity can be improved. Although this and the several other investigative areas suggested will receive attention in due course if the system recommended by this study is implemented, their investigation at this time is not required in order to permit the construction of a prototype interchange installation.

For the above system, investigation of an automatic ice sensing system is not recommended. The selected system operates to keep the roadway surface just above 32°F at all times. Although the heat penalty is thought to be significant, the gains achieved in safety are considered to outweigh this disadvantage.

IV. DESCRIPTION OF SYSTEMS STUDIED

This section presents details of the systems that were studied along with a comparison of the systems on the basis of relative costs, reliability, safety, and ease of installation. Table IV-1 shows the comparison of the systems which are tabulated in descending order of their relative ratings.

A. Nuclear With Earth Storage

1. System Description

The nuclear system derives its energy from fission product decay (Figures IV-1, IV-2, and IV-3). Capsules containing the fission products are placed in shielded tanks that contain a heat exchanger fluid. The fission product decay heat is transferred to the fluid by conduction. Electric motor driven pumps circulate the fluid through buried distribution pipes to the soil below the roadbed. Heat pipes transport the energy from the soil in the proximity of the distribution pipes to the roadbed. During summer months, the energy is stored in the soil below the soil below the road surface (the heat pipes will not pump heat to the higher surface temperature).

There is a particular advantage to the nuclear system in combination with earth storage. Even with 50% losses (conservative estimate) associated with low temperature storage and retrieval, fewer capsules are needed for a given installation than would be the case if the system were designed on strictly a demand basis. This is because the fission product heat production is determined solely by natural radioactive decay. It is not possible to turn the heat production on and off. In a demand system, sufficient capsules must be

TABLE IV-1

COMPARISON OF SYSTEMS AND RATINGS

Rank Rating	System	Cost, Normalized 1= Highest Relative Cost	Reliability 1= Highest	Safety 1= Safest	Installation 1 = Easiest	$\sum$	Rating %
1	Natural Earth	4.5	1.0	1.0	0.5	7.0	100
2	Nuclear	2.8	1.0	0.8	0.3	4.9	70
3	Electrical with Heat Pipe	1.8	0.7	0.8	0.4	3.7	53
4	Shielded Electrical Wire	1.5	0.3	0.5	0.6	2.9	42
5	Bare Electrical Wire	1.2	0.1	0.5	1.0	2.8	40
6	Fossile Fuel	1.0	0.2	0.8	0.6	2.6	37
7	Infrared	1.0	0.7	0.5	0.2	2.4	34

Cost = operating and installation costs, prorated over projected life of system then normalized

Reliability = proportional to system projected lifetime and normalized

Safety = scaled arbitrarily, weighing electrical and leakage potential

Ease of Installation = proportional to cost and normalized

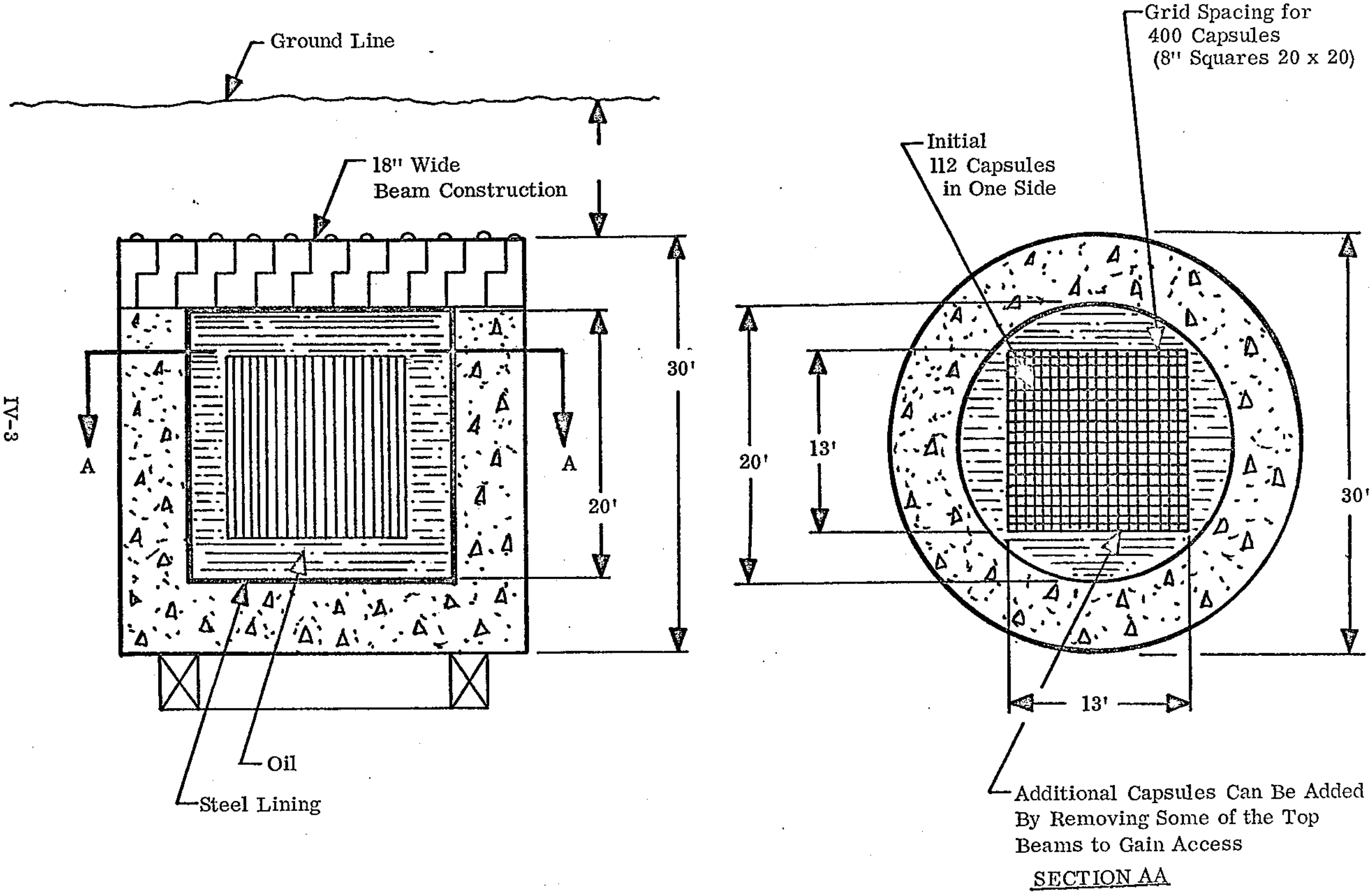


FIGURE IV-1: NUCLEAR ENERGY CONTAINER

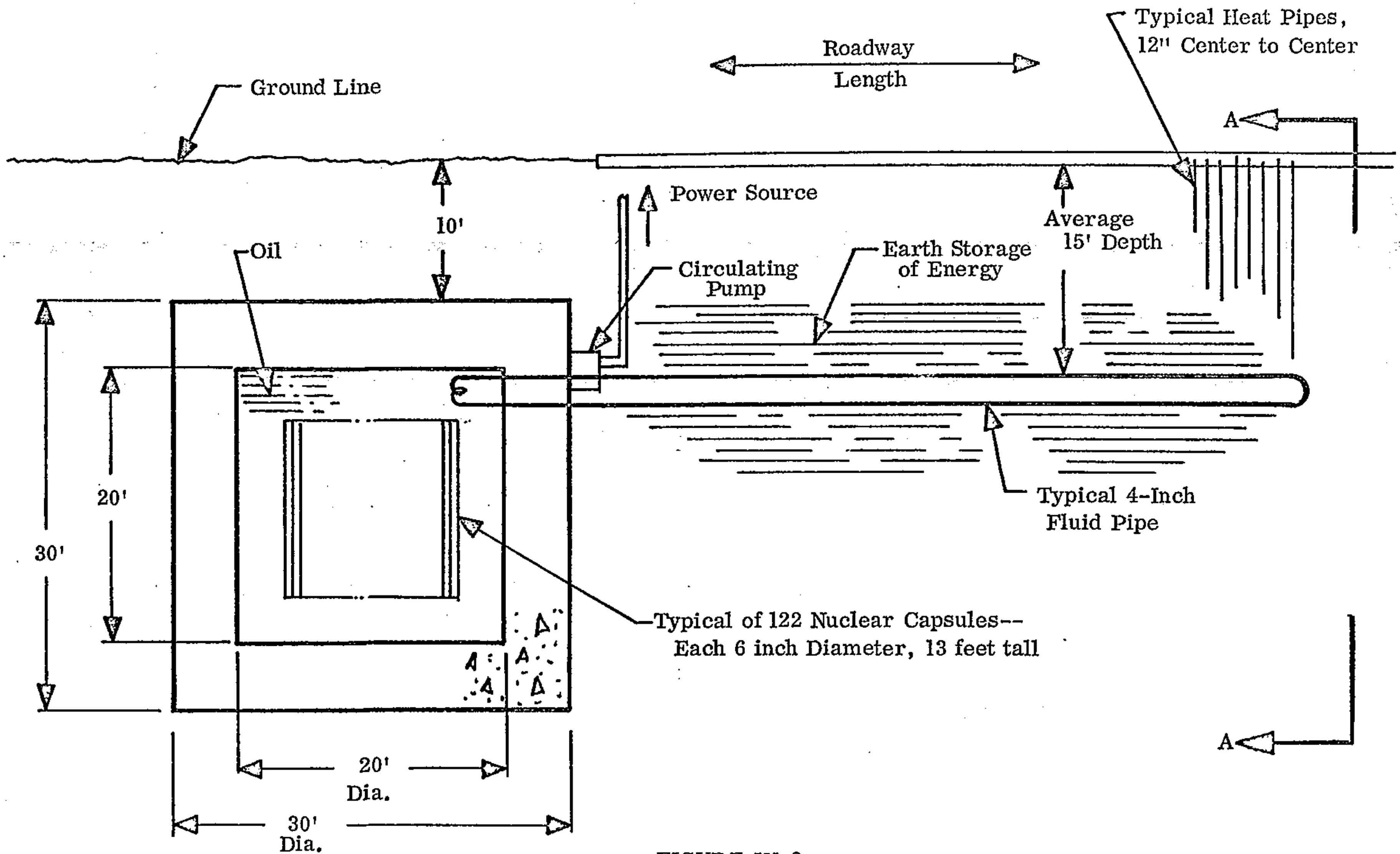
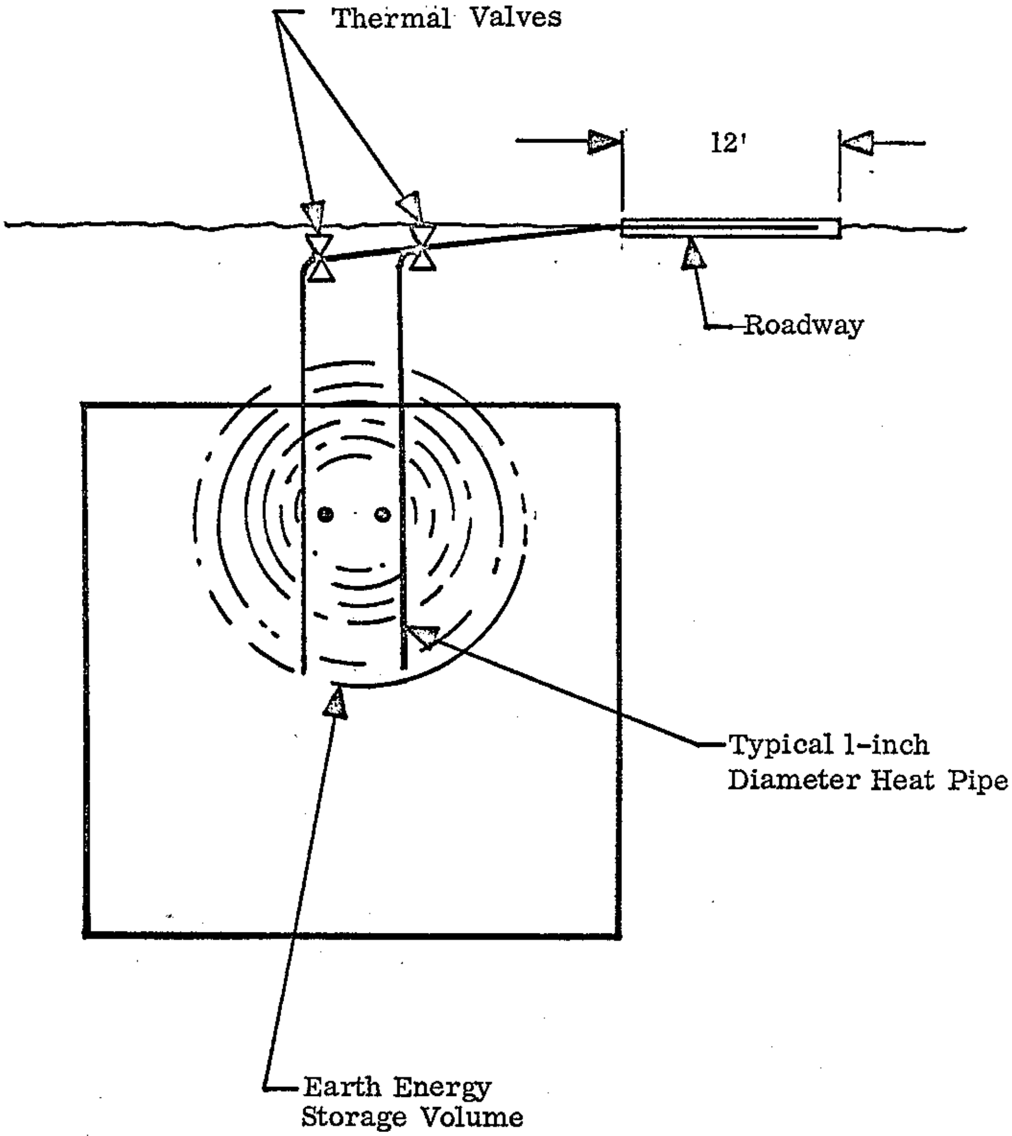


FIGURE IV-2
SCHEMATIC REPRESENTATION OF NUCLEAR ENERGY DEICING SYSTEM



VIEW A-A

FIGURE IV-3

SCHEMATIC REPRESENTATION OF NUCLEAR ENERGY DEICING SYSTEM provided to meet the peak demand; when the demand is lower or zero, the same amount of heat is still provided by the capsules. In the storage mode, with continuous energy storage, the number of capsules for a given installation can be reduced to one sixth of the number required for a demand system.

It is more economical to build a central shielded containment tank for a large number of capsules, rather than a number of smaller tanks. The breakover point was not determined. However, for a typical large interchange connecting two multiple lane expressways, a reference model was treated in which 8 ramps having a total surface area of 67,200 square feet were considered as having a nuclear earth storage system. A single nuclear installation was found to be more economical in comparison to the multiple shielded storage tank arrangements despite the shorter distribution lines required.

There will be safety provisions needed with the nuclear system. In this present study, concrete shielding was provided on all sides of the primary container and a double container liner was supplied. Emergency heat dumping was provided for by a temperature controlled heat pipe system to protect against the possibility of electrical failure on the operation of the field-distribution pumps or mechanical failure of the pumps.

The main restriction in this system is the limited quantity of fission products available; and, therefore, a small number of critical highway installations can be served. The projections of Table IV-2 are based upon the nuclear system supplying all of the energy. They are conservative on two points: (1) they do not consider a contribution from natural earth heat; (2) a 50% storage/recovery efficiency is postulated which is probably low.

TABLE IV-2

NUMBER OF TYPICAL INSTALLATIONS

Year	Storage	No Storage
1985	156	26
1990	378	63
1995	720	120

The heat pipe system utilized with the nuclear energy storage mode would be adequate without nuclear energy to supply deicing in moderate climates. In severe climates, where the recovery of the earth heat sink is less than 100% during the summer, nuclear energy would provide one logical mode of augmentation to supply the energy needed for 100% recovery of the heat sink. The amount of augmentation needed would probably not exceed 25% of the total, even in the most severe climates. If the nuclear sources are considered as auxiliary sources, providing from 10 to 25 percent of the total energy required, the number of installations would be increased as is shown in Table IV-3.

TABLE IV-3

NUMBER OF TYPICAL INSTALLATIONS (STORAGE MODE) WITH NUCLEAR ENERGY AUGMENTATION

Year	10% Augmentation	25% Augmentation
1985	1560	624
1990	3780	1512
1995	7200	2880

2. System Cost

Installed costs for nuclear heat sources were determined for various heat outputs and for loss of cooling temperature rises of $1^{o}F/hr$ and $4^{o}F/hr$.

A double wall containment was designed and included in these costs. This double containment feature might be required by the AEC to provide safety margin to protect against loss of coolant. The results of this study are presented in Table IV-4.

TABLE IV-4

COMPARATIVE INSTALLATION COSTS

No. of Capsules	1^{o}F/hr	4^{o}F/Hr
1	$ 9,250	$ 6,670
2	11,400	7,730
4	14,400	9,360
8	19,300	11,400
10	21,500	12,400
25	33,900	17,700
50	51,500	24,700
100	81,400	36,000
150	108,000	45,300

Each capsule has a power output of 1.5 KW. Therefore, a 100 capsule system has a power output of 150 KW, and this is the power level (with allowances for fission product decay) required for a typical interchange in a moderate climate. This study demonstrates that each interchange should have a single nuclear heat source rather than multiple smaller heat sources distributed around the interchange.

The costs of the installation tabulated above include the complete nuclear source container. The distribution system, consisting of pumps and fluid lines will cost between $1.10 and $1.35 per square foot of highway. The heat pipe system to transfer the heat to the roadway would cost about $4.50 per square foot. The total installed cost for an earth-storage nuclear system is therefore approximately \$7.00 per square foot. The operating costs associated with the system are very small and consist of the electrical power for the pumps and annual maintenance to the equipment. Based on 15 years minimum expected lifetime, the cost per year of the system is about \$0.47 per square foot.

3. System Assessment

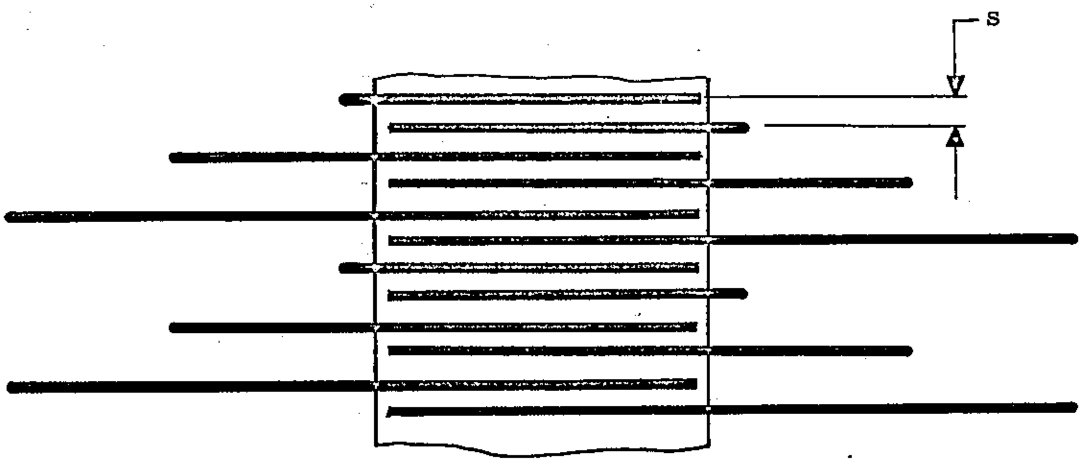
This system is more expensive than the Natural Earth Heat Pipe system. It is a logical choice for locations where severe conditions would make a natural heat pipe system marginal. With its very low operating cost, it would be especially attractive to State Highway Departments where the prorated operating cost over the expected lifetime of the system is about five cents per square foot per year.

B. Natural Earth Heat Source

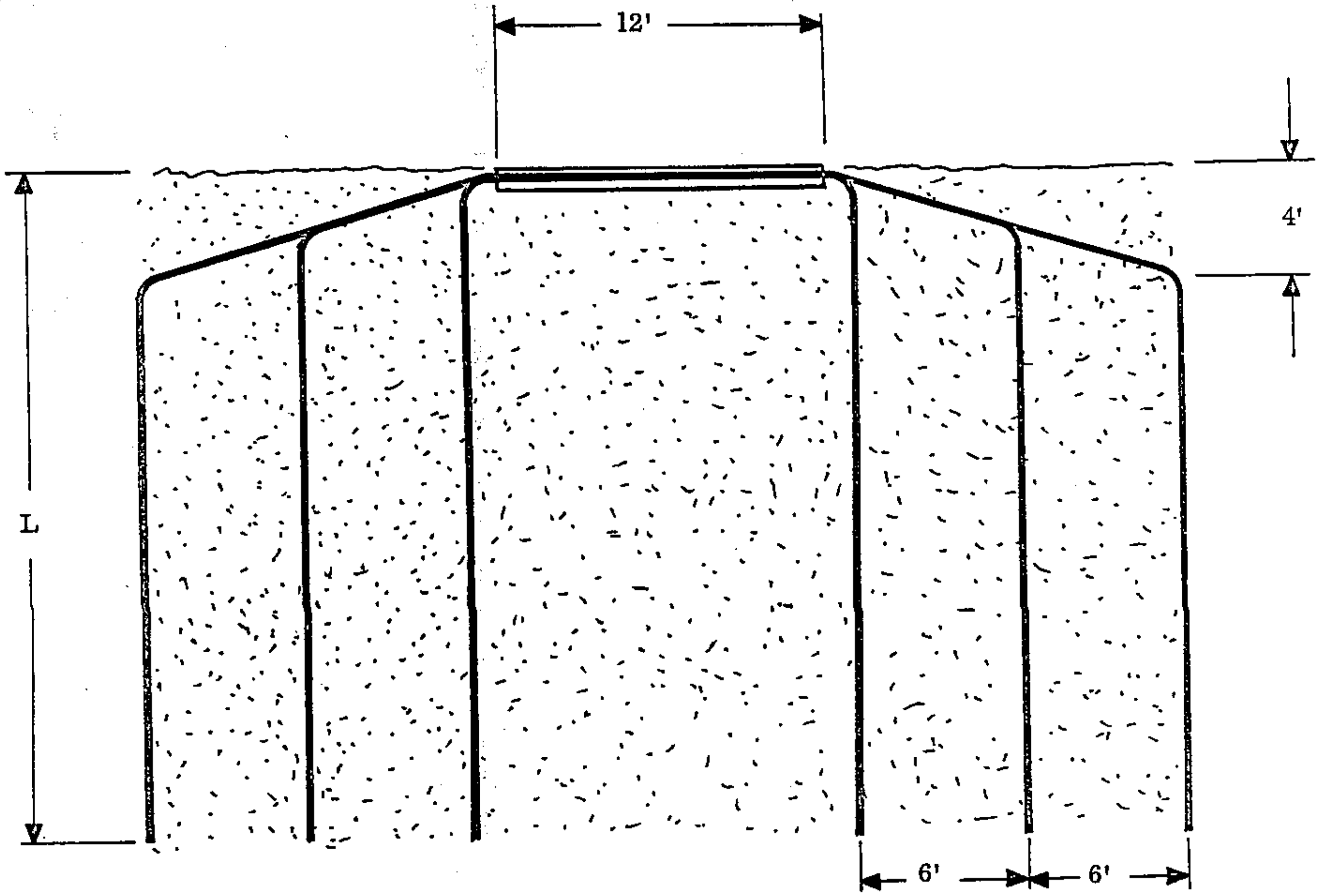
1. System Description

This system utilizes the natural heat energy of the earth as a source. Heat pipes transport the energy to the highway surface. This is a passive system with no operating costs. It is the most practical system for the majority of highway applications. Figure IV-4 shows plan and elevation sketches of a typical heat pipe installation.

Figures IV-5 and IV-6 show symmetrical and asymmetrical heat pipe earth heat exchangers for ramps in a typical interchange for moderate climate (Baltimore) and severe climate (Binghamton). The annual energy requirement in Baltimore is 26,000 BTU/year ft^2 and in Binghamton 132,000 BTU/year ft^2. The heat pipe patterns shown provide sufficient earth volume to supply the total energy requirement (permitting a $10^{o}F$ maximum drop in earth average temperature)



Plan View - Ramp



Elevation View - Ramp

FIGURE IV-4

CONCEPTUAL DESIGN - RAMP HEATING SYSTEM

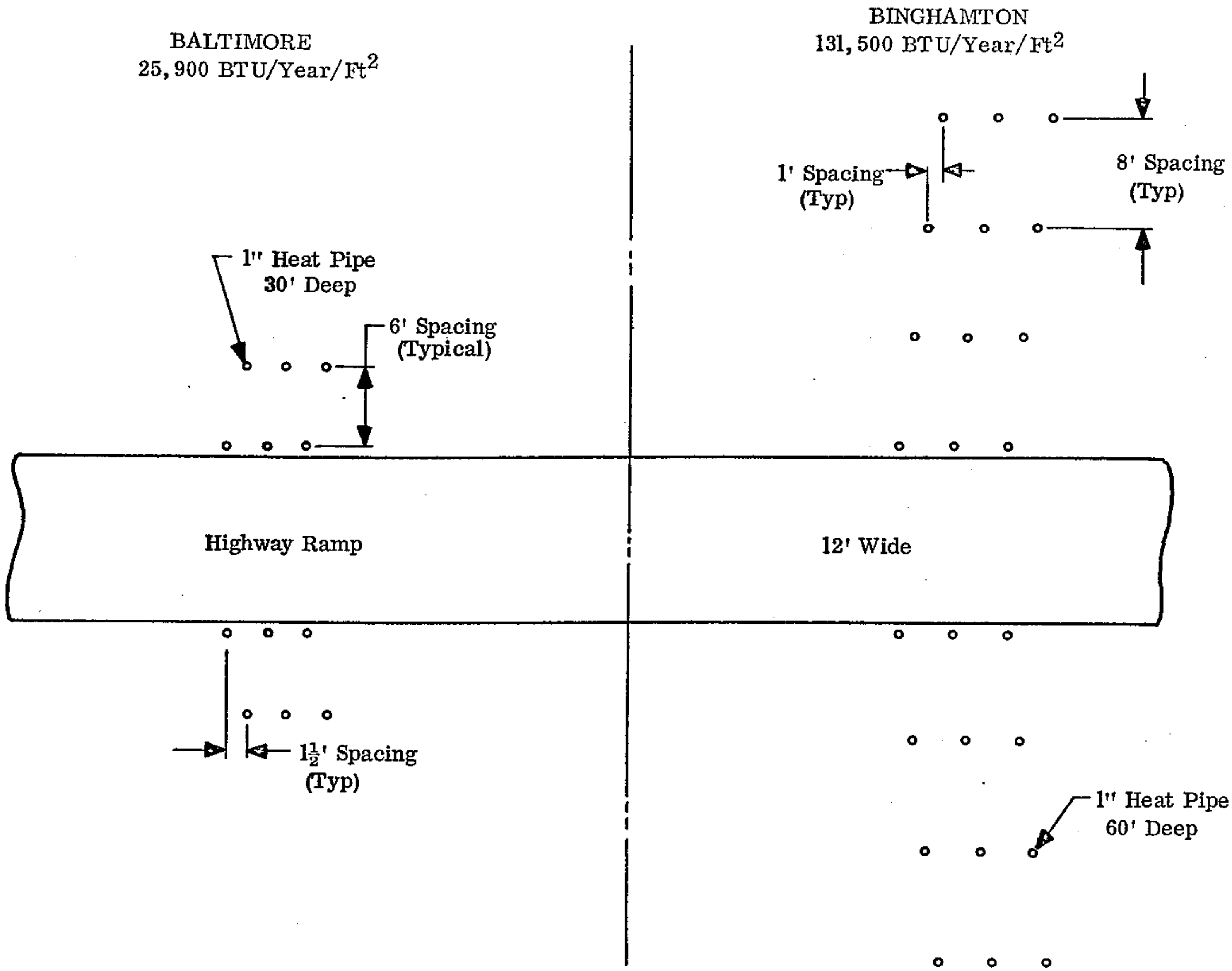


FIGURE IV-5: HEAT PIPE HEAT EXCHANGER PATTERN - SYMMETRICAL ARRANGEMENT

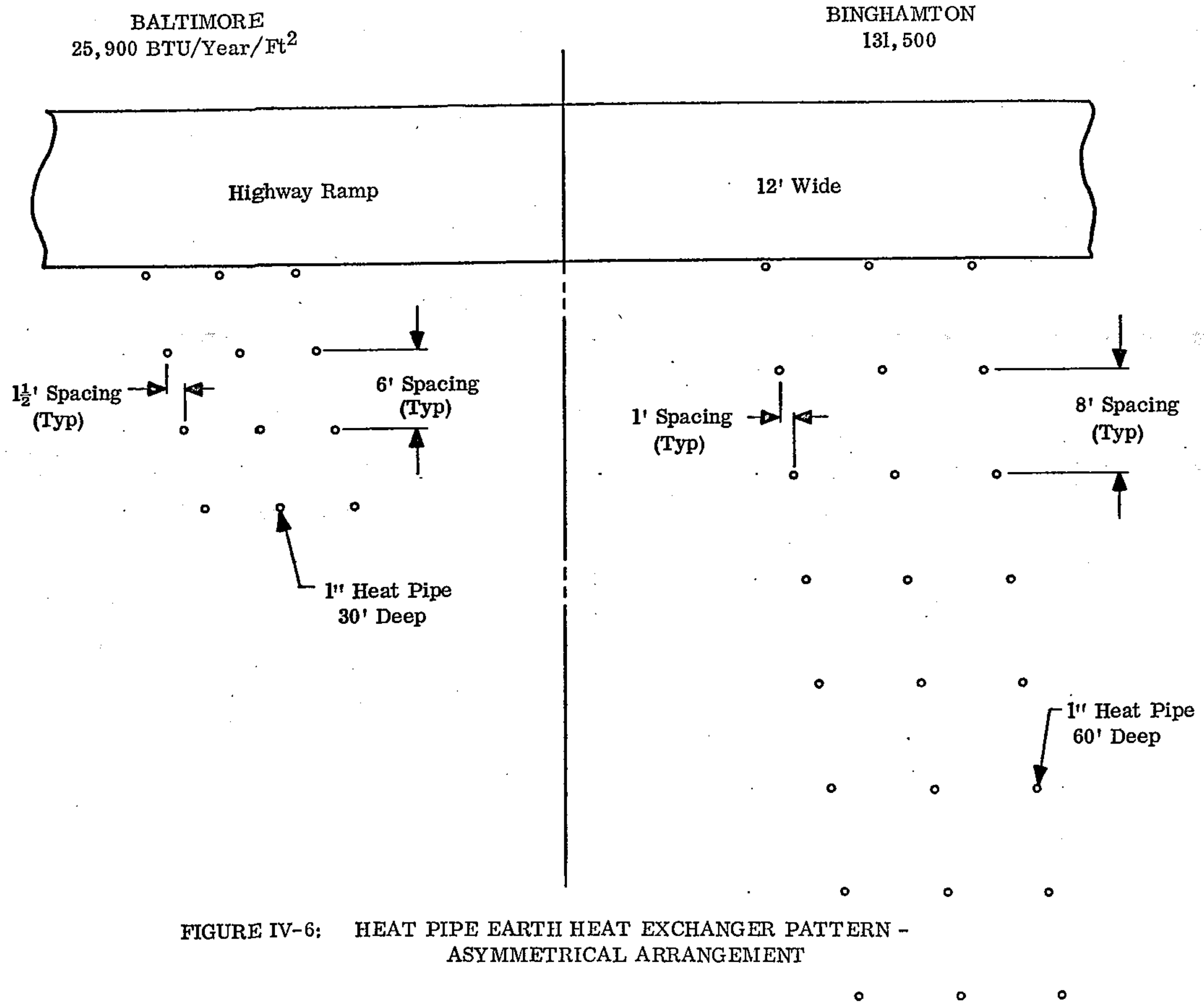


FIGURE IV-6: HEAT PIPE EARTH HEAT EXCHANGER PATTERN - ASYMMETRICAL ARRANGEMENT for the representative interchange. Complete summertime temperature recovery for either pattern for Binghamton might be marginal. Analytical and experimental data show that, for a 30^{o}F drop in earth average temperature, summertime recovery of a 20' x 75' by 14' deep block is complete, whereas the recovery of a 20' x 75' by 24' deep block is about 82%.

2. System Cost

Cost of the heat pipe installation includes the cost of the heat pipes themselves, installing them in the ground, and the emplacement of the pipes in the concrete. The field operations are not unusual to current construction practice and will not present any major new problems to highway contractors. The heat pipes will be assembled at the factory and delivered to the site ready to install. The heat pipe and thermal valve represent 44% of the cost; the hole and emplacement account for the other 56%.

3. System Assessment

The heat pipe system is the most economical, based on prorated lifetime costs. There are no annual operating costs, and the units are inherently reliable and safe. Because the system is designed to maintain the highway pavement above 32^{o}F at all times special ice sensing equipment is not required. In addition, the system operates at a relatively low temperature--that is, the ambient temperature of the earth--therefore it lends itself directly to efficient energy storage by alternate energy sources such as nuclear waste heat.

C. Electrical With Heat Pipe Mat

1. System Description

In this system (Figure IV-7) the electrical energy is applied to high-

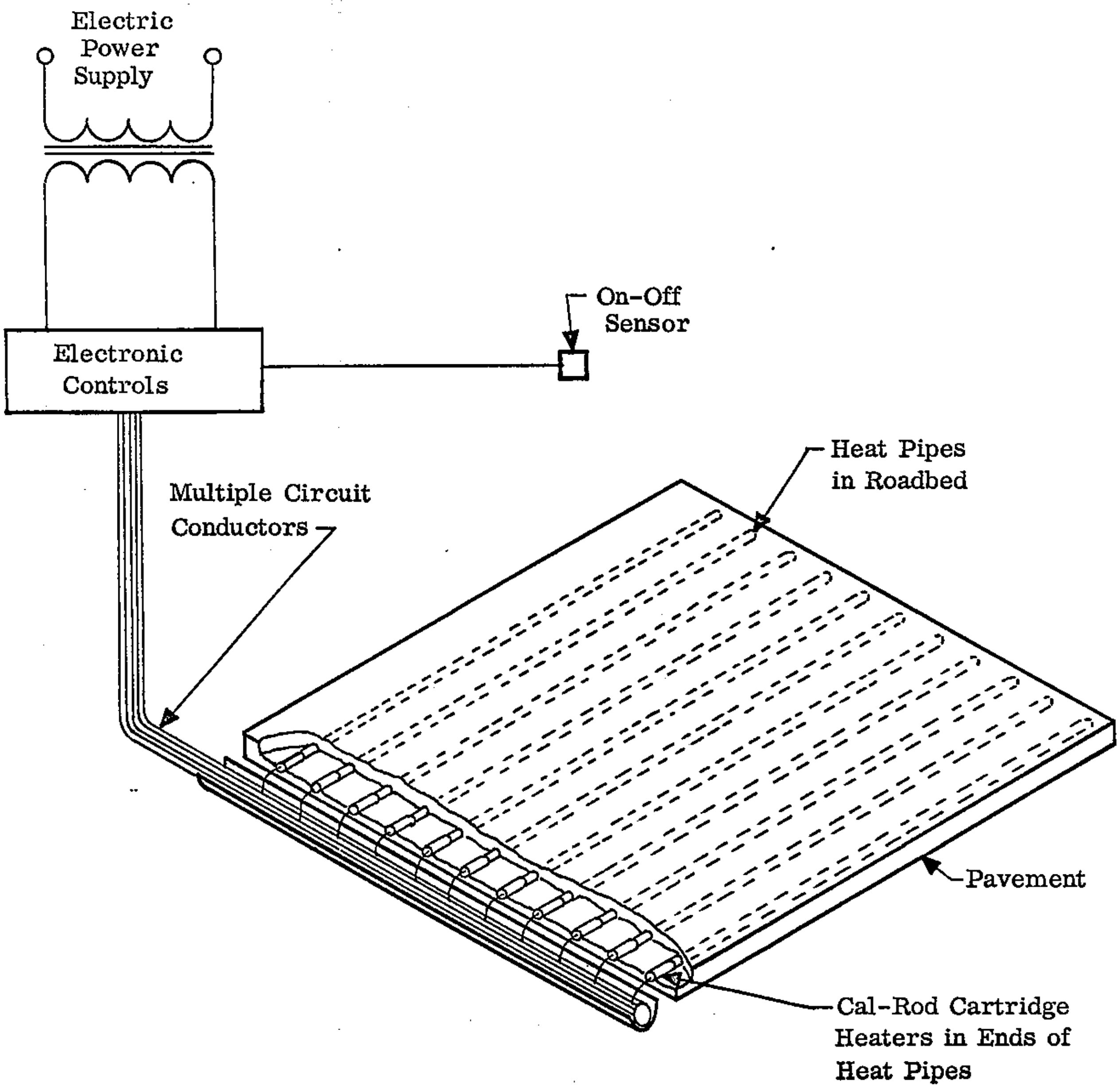


FIGURE IV-7

ELECTRICAL WITH HEAT PIPE MAT

reliability heater cartridges, which are installed in the ends of heat pipes that distribute the heat to the pavement. Conceptually, it appears feasible to arrange the heaters for field replacement, should this become necessary. The advantage of this system is that the electrical lines and elements are not embedded in the roadway, thus eliminating many of the previous causes of failure in electrical systems either as a result of installation or as a result of corrosion.

The heaters would be arranged in separate circuits so that electrical failure to one bank of units would not completely cut service to an entire section of pavement. A high voltage system is favored (220 to 440 volts) in order to reduce conductor cost and transmission power loss.

2. System Cost

Installation cost of this system has three components: the heat pipes, the cartridge heaters, and the electric distribution system. There is also an annual operating cost. The installation of this system is similar to that for the shielded wire electric system in regard to ice sensing instrumentation, electric lines, etc. The same cost ($4 per square foot of highway) is applied, plus the cost of heat pipes and sealant for the cartridge heaters ($2 per square foot of highway). The electrical costs are derived as described in section V-H.

3. System Assessment

The system offers a much better reliability than systems which have heater wire embedded in the highway pavement. The cartridges are high reliability units, and the mode of installation provides a good assurance of protection from environmental effects. Because of the improved life expectancy the prorated cost is lower than for the wire in pavement systems, giving this system a superior evaluation.

D. Mechanical/Chemical

1. System Description

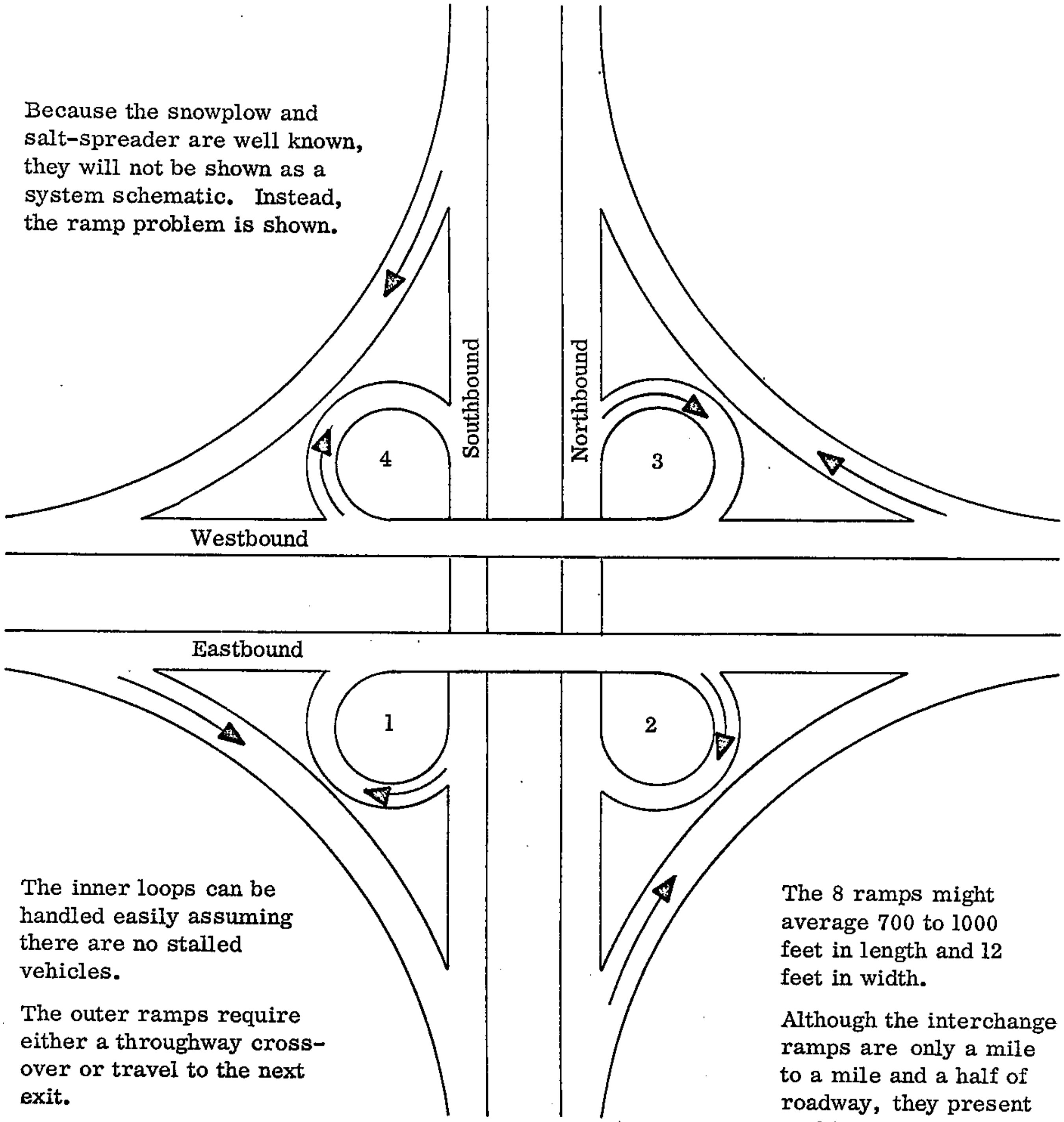
This system is the major one in service today. It entails side effects that are not possible to assess. The snow plow damages roads by mechanical action. The adverse effects of salt on the pavement have been under investigation. (The corrosive effects of salt on public automobiles is well known.) The steady application of large quantities of salt into the local environment is a matter of concern and is also under investigation.

It is difficult to assess the actual cost of this mode of removal because there are maintenance, administrative, and capital cost depreciation expenses that cannot be separated out easily.

In operation, the presence of traffic complicates the problem of plowing or salt spreading (Figure IV-8). This becomes an acute problem on access ramps, if a vehicle is stalled with a stackup in back of it. The snow removal equipment also suffers breakdowns, and a disabled plow results in an extraordinary delay in opening a road.

2. System Cost

It has not been possible to obtain meaningful cost data for interchange snow and ice removal. Estimates range from 1 to 30 cents per square foot per year. It has been proposed that two men and a plow stationed at a troublesome interchange during the winter can provide the equivalent capability as an automatic deicing system. Assuming this to be true, a labor cost of $15/hour for



Because the snowplow and salt-spreader are well known, they will not be shown as a system schematic. Instead, the ramp problem is shown.

The inner loops can be handled easily assuming there are no stalled vehicles.

The outer ramps require either a throughway cross-over or travel to the next exit.

The 8 ramps might average 700 to 1000 feet in length and 12 feet in width.

Although the interchange ramps are only a mile to a mile and a half of roadway, they present problems to mechanical removal or salt spreading.

FIGURE IV-8

MECHANICAL/CHEMICAL

a period of 1000 hours would represent an annual cost of $15,000 per interchange (22 cents per square foot for the typical interchange selected for this study). This time may be excessive for moderate climates (Baltimore has approximately 6 days snowfall per year) and may be inadequate for severe climates (Binghamton has about 36 days snowfall per year). Adding to this basic labor cost, the costs for equipment depreciation, materials, and the added cost of maintenance due to chemical damage to the pavement, several cents per square foot per year may be added. On the above basis, an annual cost of 30 cents per square foot appears reasonable for a comparable manual snow and deicing capability.

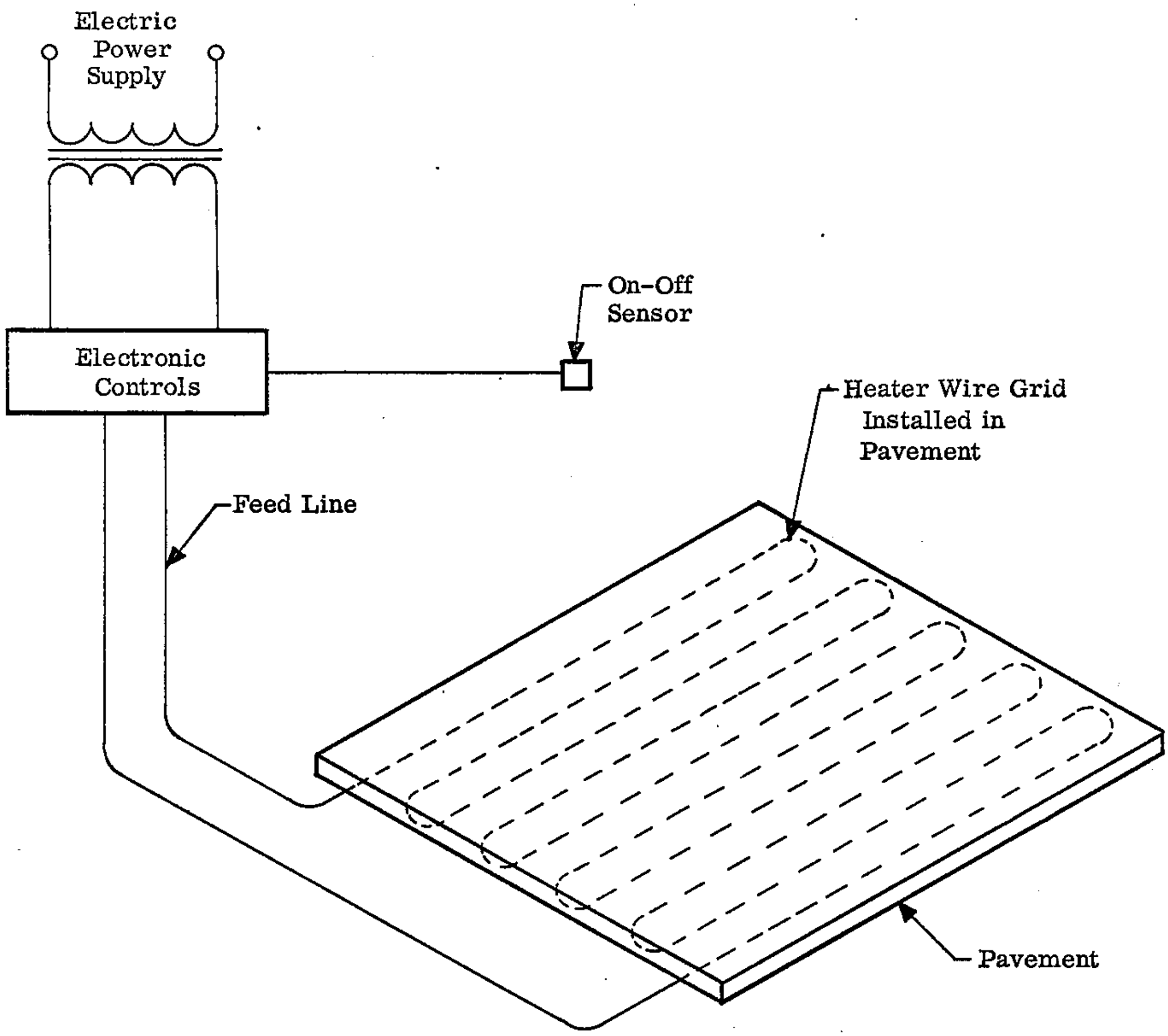
3. System Assessment

There is only one basis for comparison of the mechanical/chemical systems with the automatic systems, and this is cost. If a weighted number of 30 cents per foot square is considered realistic for mechanical/chemical systems, this cost is equivalent to the prorated lifetime cost of the Natural Earth Heat Pipe System. On this basis alone, the choice would favor the automatic system. It is a well-established fact that decisions made in the past to automate mechanical processes have resulted in further rapid improvements in performance and cost over those estimated for the first prototype system.

E. Shielded Electric Wire

1. System Description

In this system, shielded resistance wire is embedded in the roadway (Figure IV-9). Voltage used in typical installations is 240 volts. The system



This system can operate on high voltage (220-260 V A-C)

FIGURE IV-9

SHIELDED ELECTRICAL WIRE

is generally satisfactory in snow melting. It requires a control system to turn on and off, otherwise the operating cost becomes prohibitive.

The system is subject to damage from a number of sources. It is vulnerable to breakage during installation of the roadway. During service, corrosion and shear stresses are encountered; and, as a result, water seeping into the insulation causes short circuits, open circuits and grounds.

A system in Salem, Oregon, operated from 1953 until 1960, at which time damage and degraded performance were observed. The system was abandoned in 1963 due to unserviceability. This system consisted of 1/4-inch lead covered resistance cable buried 2 inches deep in the pavement and spaced from 4-1/2 to 1-1/2 inches. (Closer spacing under wheel tracks.) It had automatic control. The installation covered 12,450 square feet and required 150 KVA at 204 volts.

2. System Cost

Cost data reported for the system were obtained from the literature. The installation cost of $4 per square foot of highway is low, because costs of materials and labor have climbed steadily since the data were reported. The operating costs are based upon reported values, rather than the current rate structure reported in section V-H.

3. System Assessment

Experiments in the application of heat to highways by electrical means showed that the general approach is technically feasible. Operating costs are high; and the systems are susceptible to wire breakage due to concrete cracking, and to shorting due to moisture.

F. Fossile Fuel Heat Source

1. System Description

This system utilizes gas or oil fired furnaces with boilers, and/or surge tanks, and pumps to produce either the required electric power or source of heat for the transport liquids.

In this study, we have considered the fossile fuel source as a fluid heater (Figure IV-10) not as an electrical energy producer. The fuel is supplied either from mains or tanks.

This type of system requires maintenance and is susceptible to failure at a critical time in the snow season.

The implications of adding to air pollution have not been evaluated but would be a factor in planning this type of system.

2. System Cost

One-third of the installed cost for this system is that associated with the field piping and its associated trenching; the other two-thirds of the installed costs represent the plant, boiler and feeder pipes. The reported operating costs of two cents per square foot provide fuel but not maintenance and stationary engineer services.

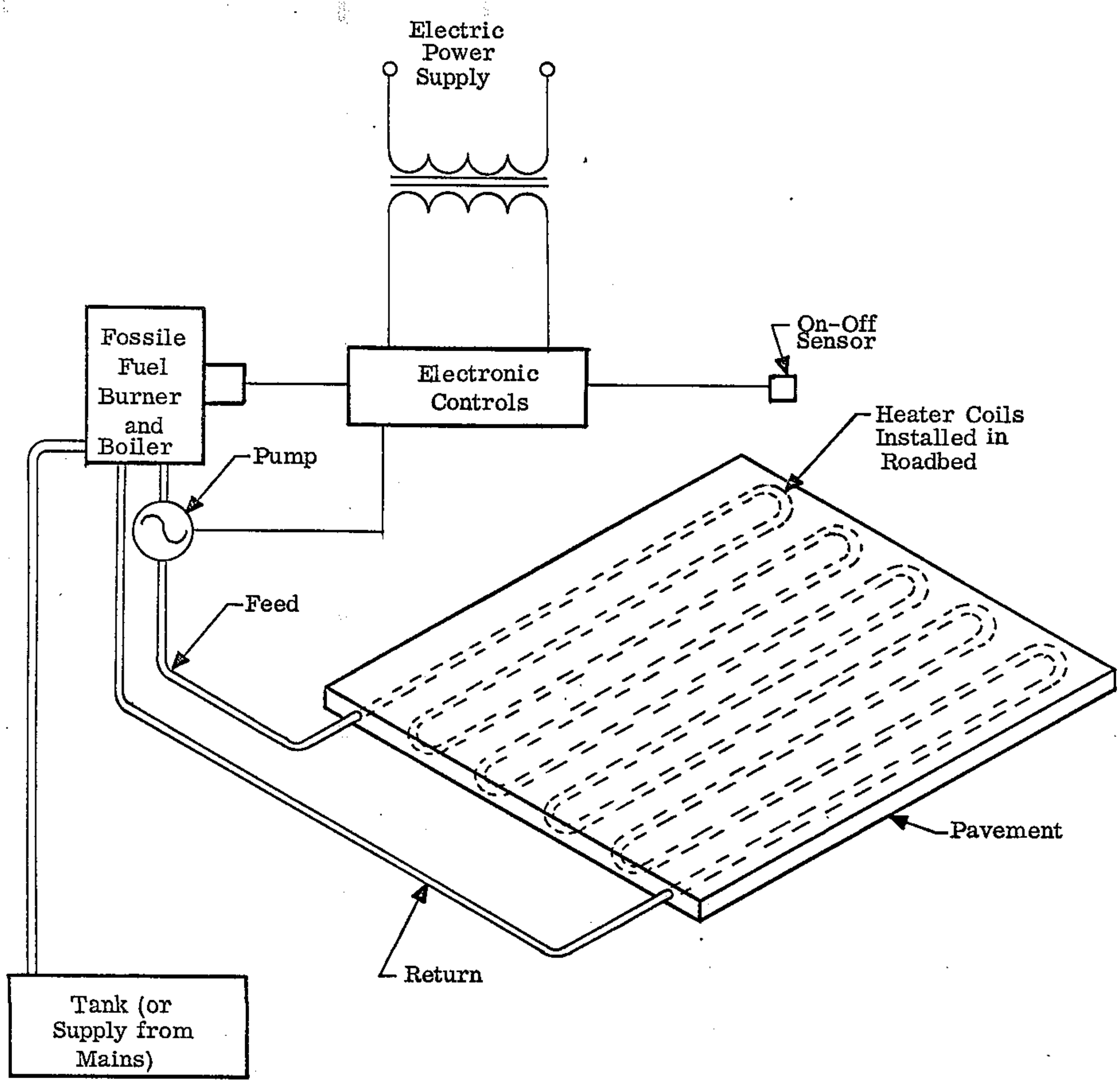
3. System Assessment

The system is rated relatively low, because of its relatively high pro-rated cost and low reliability.

G. Infrared

1. System Description

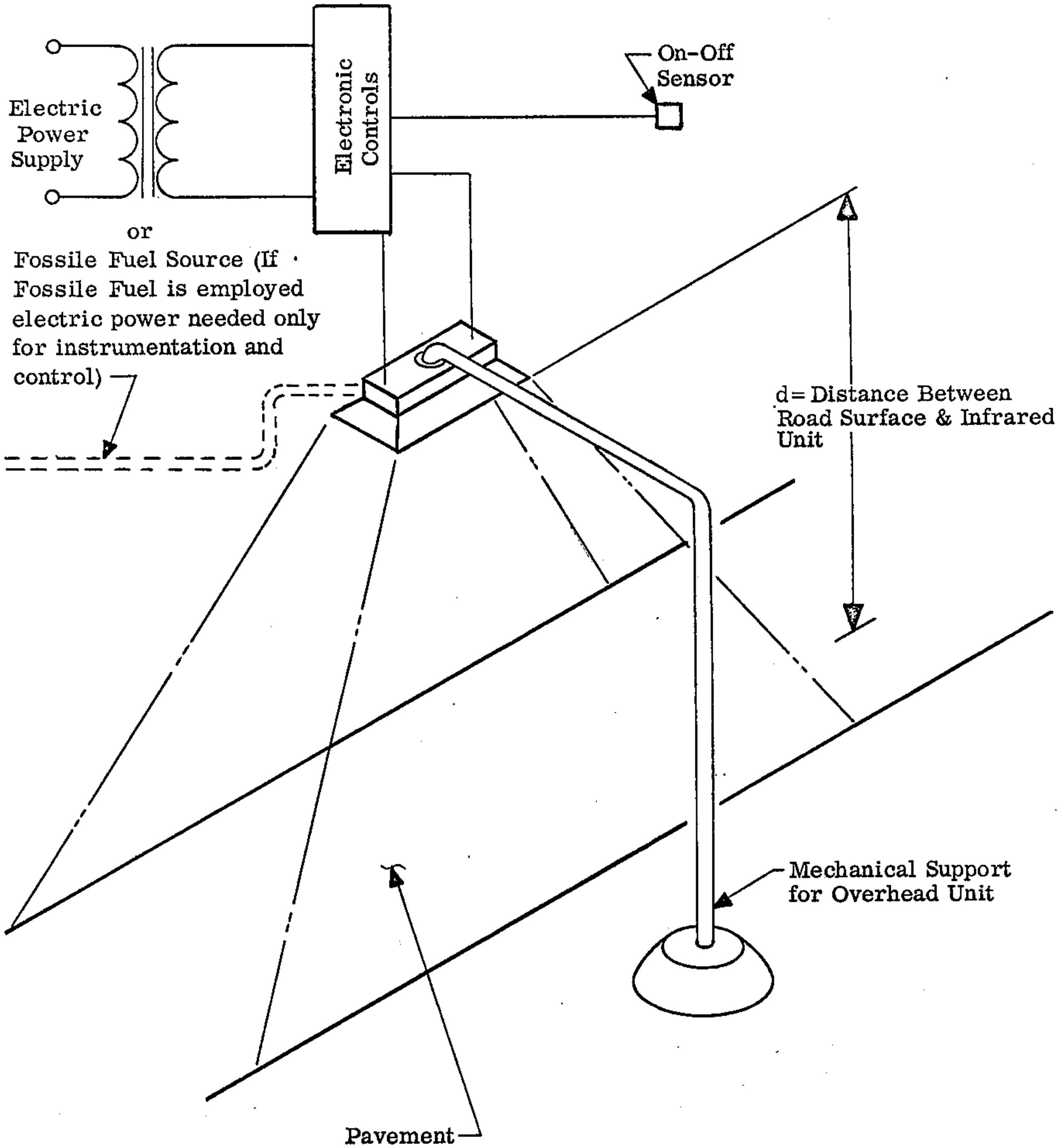
The infrared heat source system (Figure IV-11) can be powered either by



This type system is greatly improved from a maintenance standpoint, if an ample quantity of isolation valves are included.

FIGURE IV-10

FOSSILE FUEL HEAT SOURCE



1. As distance d is increased, efficiency of unit is reduced.
2. If unit is closer than 23 feet, it endnagers vehicles that are halted beneath it.
3. Does not require rework of pavement for installation or replacement.
4. Must be turned on prior to accumulation of reflective snow layer.

FIGURE IV-11

INFRARED DEICING SYSTEM

electricity or by fossile fuel. It is not well adapted to mounting close to the roadway. If it is mounted at the side of a road or a bridge deck, there is a considerable disadvantage to beaming the rays across the roadway because of intensity variation. If the units are mounted above the road, the support structures are extensive because they must be placed at a 23-foot height so that vehicles that halt beneath them will not be damaged. Because the intensity of the beam (on the centerline of the unit) decreases as the inverse square of the distance, the units require close spacing and a large amount of energy. (To provide 100 BTU/ft^2 to an area 100 x 54 feet, 70 units, 23 feet high, are needed, each producing 48,000 BTU.)

An infrared system must be turned on before snow accumulates, otherwise reflection from the snow makes the energy unavailable to the roadway.

The gas fired units produce the most satisfactory wavelengths for heat absorption in the concrete, and there is less of a problem with the reaction of the unit to precipitation.

A variation of the infrared system has been proposed, but not tested, for bridge deck application. The units would be mounted beneath the bridge structure. This type installation eliminates many of the disadvantages of the overhead installation and would have a lower installation cost.

2. System Cost

The infrared system is expensive to install and to operate.

3. System Assessment

The one advantage of the system is that it can be installed without disturbing the highway pavement. The below-deck application in bridges deserves additional evaluation. However, with the narrow space available under the bridge deck, the range of the unit will be restricted. If the units are moved further away, the same disadvantages of cost reported for the overhead installations will be created.

H. Bare Electrical Wire

1. System Description

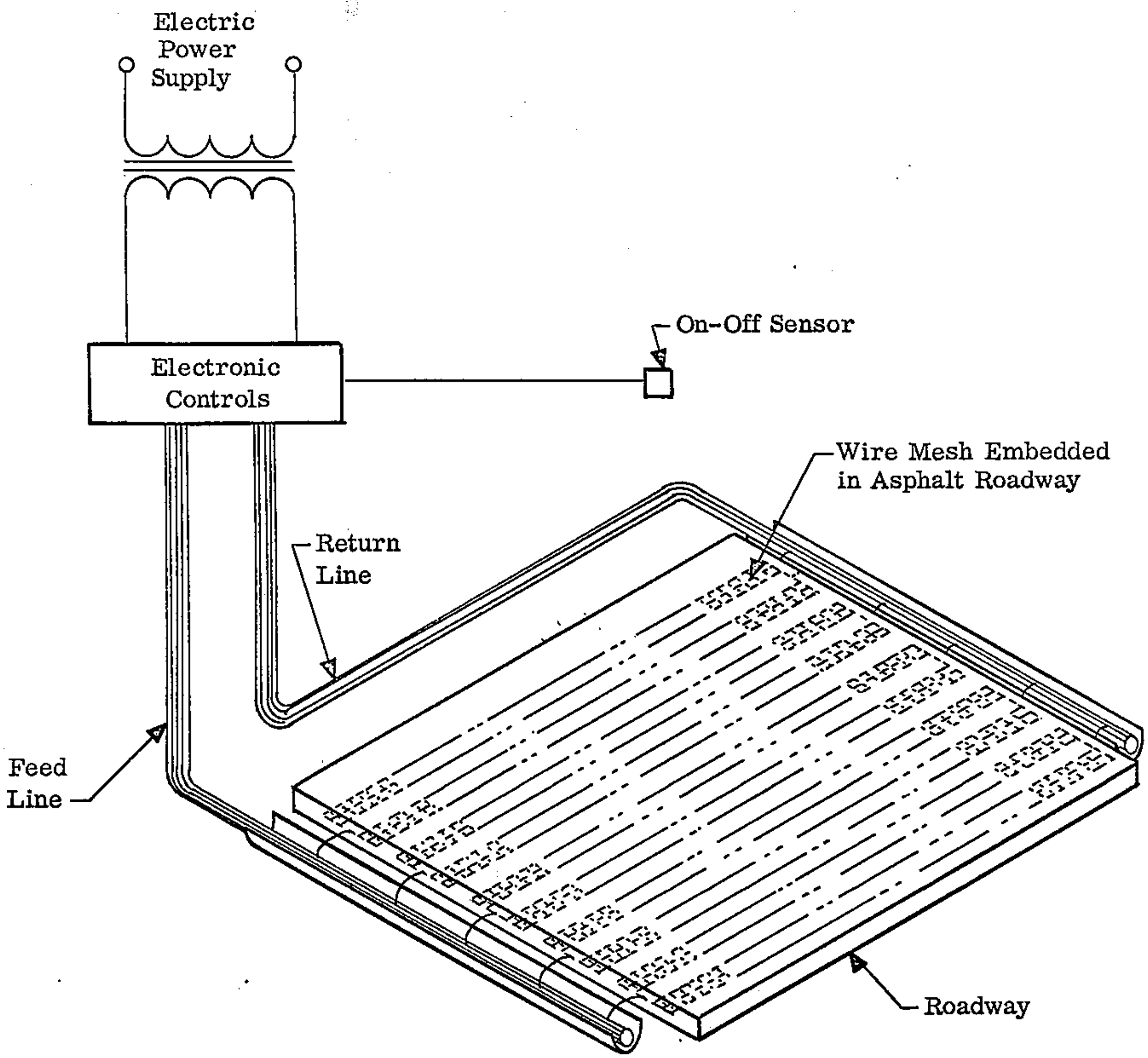
This system (Figure IV-12) utilizes wire mesh as the electrical resistance element. It is not suitable, generally, for emplacement in concrete; but it has been applied to asphalt roads. It is a low voltage (40 to 50 volts) system, which results in large power losses unless feeder lines from transformers are short. It is very susceptible to moisture damage; and, unless it has an on-off control system, the operating costs are excessive.

2. System Cost

The cost of installation reported for this system is relatively low, as is the operating cost. The life expectancy is short. It is believed that the costs, based on current prices, would show the cost of this system to be closer to that of the shielded wire system.

3. System Assessment

This system is especially susceptible to damage by concrete cracking and by moisture. Considerable care is recommended by manufacturers of the wire mesh during installation to protect the elements from breakage. Manufacturers also express great concern for adequate drainage to avoid contact of the mesh with freezing water.



1. This system is applicable to asphalt roadbeds.

2. The system operates on low voltage (40 to 50 Volts) so line losses can be significant unless lines from step down transformer to road are short

FIGURE IV-12

BARE WIRE ELECTRICAL DEICING SYSTEM

V. TECHNICAL DISCUSSION

A. Maximum Power and Energy Requirements

The maximum power that must be supplied by the heat source is dependent upon the following factors:

1. Prevailing climatological conditions (geographic location)
2. Classification of snow and/or ice prevention system employed
   a. Complete melting of snow as it falls or ice as it forms on the roadway.
   b. Prevention of snow freezing to the road surface.
   c. Prevention of preferential icing of critical surfaces.
3. Temperature of the heat source employed - transport losses

   As an example, conventional systems using circulating fluids generally operate above 150^{o}F and, consequently, experience back losses to the earth of as much as 30% of the total heat required for melting. In comparison, a system using natural earth as the heat source experiences essentially no losses.

Nominal power requirements have been established for the three classifications of systems taking into account factors 1 and 3.

1. Total Snow Melting and Deicing

Power requirements for the melting of snow, without allowing any accumulation, have been established for the entire U. S. by Adlam (Reference V-1). For the states being considered, depending on the location of the installation, the power requirement corresponds to melting snow falling at a rate of 1.5-3.0 inches/hour. However, analysis of the climatological data, along with other studies made (Reference V-2), indicates that only one-third of this amount is necessary for keeping the surface free of snow approximately 90% of the snowfall hours. The power requirement associated with complete melting 90% of the time has been defined as the nominal design condition. It will be shown later that in the few instances when this nominal power would be inadequate for total melting that it would nevertheless be sufficient to prevent the snow from freezing to the road surface. Thus, in the extreme cases snow removal by conventional equipment would be facilitated. The nominal power requirement for a system utilizing a low temperature heat source thus becomes 12.5 - 25 W/ft^2 depending on the location of the installation. In cases where a high temperature heat source is used, the heat distribution system will experience as much as 30% losses back from the roadway to the ground. In addition, there will also be transport losses in getting the heat from the heat source to the heat distribution system in the roadway. The transport losses are assumed to be 10% of the total heat. With both of these losses taken into account, the power requirement for a high temperature heat source becomes 18-36 W/ft^2.

2. Prevention of Snow Freezing to Roadway Surface

The prevention of snow freezing to the roadway surface has been proposed as a possible alternative to total snow melting. The various states all have snow removal equipment and, very often, it is only in severe storms that this equipment becomes ineffective. This type of heating system would eliminate the use of salts, which cause deterioration of the roadway, and would also facilitate snow removal by conventional equipment.

It was assumed in arriving at the power requirements for this condition that heat would be dissipated to the ambient from a 1" layer of snow above the roadway surface, which was maintained at 33°F. This is a conservative assumption since accumulation of snow above 1" would serve as additional insulation and further reduce heat losses to the ambient. The heat loss was determined by simultaneous solution of the following equations:

$$q = \frac{k\ (33 - T_s)}{\Delta X} \tag{V-1}$$

$$q = h\ (T_s - T_a) \tag{V-2}$$

where

q = Heat loss (BTU/hr-ft^2)

k = Thermal conductivity of snow conservatively taken to be 0.242 BTU/hr-ft-°F

h = Forced convection heat transfer coefficient (BTU/hr-ft^2-°F). This is a function of the wind velocity.

T_a = Ambient air temperature (°F)

T_s = Temperature at top surface of the snow cover (°F)

ΔX = Depth of snow cover (inches)

The heat losses are shown in Figure V-1 as a function of ambient air temperature and wind velocity. A system of this type should be designed to function under extreme conditions. The climatological data indicates that in areas with severe climates the extreme conditions correspond to 0°F ambient and 40 mph winds. From Figure V-1 the heat dissipated at the surface is approximately 23 W/ft^2. If a high temperature heat source is employed the system would experience

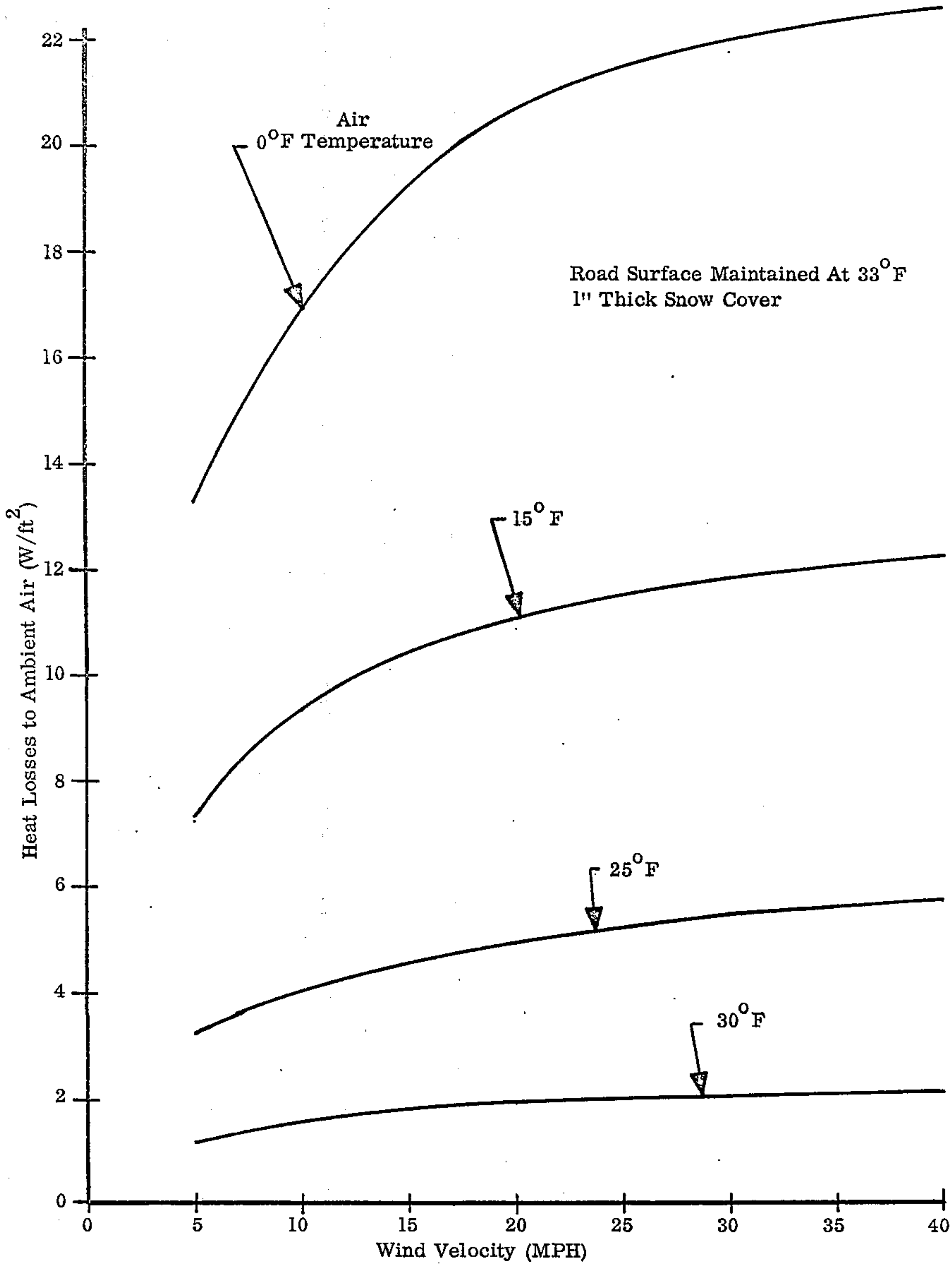


FIGURE V-1: FORCED CONVECTION HEAT LOSSES TO AIR FROM ROAD SURFACE WITH 1" SNOW COVER essentially the same losses as a snow melting system. Since power requirements for snow melting 90% of the time and prevention of snow freezing to the surface in the remaining extreme cases are almost equal, the two classifications were combined. The nominal power requirement for either classification was defined as that corresponding to complete snow melting 90% of the time. Power requirements for deicing are essentially the same as for prevention of snow freezing to the surface. The problem of deicing affects only the total energy requirements of the system, since the system must not only supply power during periods of snowfall but also whenever icing may occur.

3. Prevention of Preferential Freezing

A possible alternate to absolute snow and ice removal is the elimination of early freezing of certain critical surfaces, such as bridge and ramp surfaces. To accomplish this, heat must be added at a rate which will cause these surfaces to achieve temperatures equal to or slightly greater than the roadway surfaces in the same vicinity at the same time.

The underside of a conventional roadway surface is thermally coupled to a virtually infinite constant temperature heat source-sink. If heat were delivered to the bridge surface from the ground during periods of incipient freeze-up, preferential freezing would not occur. The amount of heat which must be supplied to the bridge pavement in order to duplicate the heat input from the ground to a roadway was estimated in the following way. Periodic temperature changes on the surface of a road penetrate into the ground with an exponentially damped amplitude. At a depth D (comparable to the thickness of the bridge) the heat flow and temperature fluctuations are reduced corresponding to

$$q_D = e^{-mD} q_s \qquad \text{(V-3)}$$

where q_s and q_D are the heat fluxes at the surface and at a depth D, respectively, and m is defined as

$$m = \sqrt{\frac{\pi}{\alpha \tau}} \qquad \text{(V-4)}$$

with α = Thermal diffusivity of the ground ~ 0.024 ft^2/hr

τ = Time constant for periodic fluctuation

Using a depth of 1 foot and a time constant of 24 hours, which is associated with daily temperature fluctuations, the heat exchanged with ground becomes

$$q_D = e^{-2.3} q_s = 0.1 q_s$$

The heat exchange at a level of 1 foot below the surface is therefore only 10% of the requirements at the surface. Thus, as a first approximation, it can be assumed that the effect of the ground in an ordinary roadway can be simulated by supplying heat to the bridge at a rate equivalent to 10% of the heat exchanged at the road surface. Similarly, the energy requirements are 10% of those for the roadway melting and deicing system. Power requirements are summarized in Table V-1.

TABLE V-1

SUMMARY OF NOMINAL POWER REQUIREMENTS (W/ft^2)

Classification of System	Moderate Climate: High Temp. Heat Source	Moderate Climate: Low Temp. Heat Source	Severe Climate: High Temp. Heat Source	Severe Climate: Low Temp. Heat Source
Snow melting and/or deicing	18.0	12.5	36.0	25.0
Prevention of preferential freezing	1.8	1.25	3.6	2.5

Aside from being related to the three factors mentioned above which affect the power requirement, the total energy requirement is also dependent upon the duty cycle and for some energy sources (e.g., nuclear) upon the efficiency of energy storage. The duty cycle is determined by the type of sensing device used to activate the snow and ice removal system. Storage efficiency is related to the heat source temperature and/or the material comprising the storage reservoir.

Nominal energy requirements have been determined for a natural reservoir-heat pipe transport system (no losses) for Baltimore (Maryland) and Binghamton (New York). These cities were selected because they have moderate and severe climates, respectively, and also available weather data. Average daily temperatures for each city for the year 1969 were used in performing the calculations. It was assumed that a temperature sensing control device would be used which would permit pumping by the heat pipe transporter only when the roadway surface temperature was 32^{o}F or less. Energy requirements were calculated assuming an average heat transfer coefficient of 5 BTU/hr-ft^{2}-^{o}F for the winter season and a surface temperature of 32^{o}F. Since average daily temperatures were used, it was also assumed that the period of heat dissipation was 24 hours on those days when the average ambient temperature was 32^{o}F or less. Energy dissipation by month is listed in Table V-2 for the two cities. The results show that there is a significant difference between the energy dissipated for severe and moderate climates. In terms of a storage system the results indicate that almost 5 times as much storage volume must be made available for a given temperature driving potential in areas where severe weather conditions prevail. A reliable snow-icing sensing control could appreciably reduce these requirements.

TABLE V-2

ENERGY DISSIPATION FOR AN EARTH STORAGE-HEAT PIPE TRANSPORT DEICING SYSTEM

Month	Energy Dissipated (Kw Hrs/ft^2) Baltimore	Binghamton
October	0	0
November	0	1.09
December	2.42	10.05
January	4.4	12.05
February	.59	9.05
March	.215	5.75
Total	7.625	37.99

In cases where systems are used which employ energy storage, the total energy requirement would be increased by a factor of 1/storage efficiency. Since storage losses increase as the temperature of the storage reservoir is increased, low temperature heat sources should be employed in order to minimize total energy requirements. In addition, heat distribution and transport losses associated with a high temperature system will also significantly increase the total energy required.

B. Significance of Concrete Thermal Conductivity and Methods of Augmenting Low Conductivity

The operating temperature of the heat distribution system and therefore of the heat source is related to the conductivity of the pavement material and the depth at which the heat distribution system is located below the roadway surface. If the distribution system can be assumed to be uniform and planar its temperature will be given by

$$T_{HD} = T_P + \frac{d}{k} q_s \qquad \text{(V-5)}$$

where d = Depth of heat distribution system below the roadway (ft)

k = Thermal conductivity of roadway material above the mat (BTU/hr-ft-^oF)

q_s = Heat flux dissipated at the roadway surface (BTU/hr-ft^2-^oF)

T_{HD} = Temperature of the heat distribution system (^oF)

T_P = Temperature of the roadway surface (^oF)

It is desirable to utilize low temperature systems since losses for such systems are almost negligible and, in cases where energy storage is employed, the storage efficiency is greatly increased. This implies locating the heat distribution system as close to the surface as practical in terms of structural considerations and using roadway materials which have good thermal conductivity. Strength characteristics of conventional concretes are such that the heat distribution system should be located no less than two inches (2") below the surface. A typical value of conductivity for concrete is 0.75 BTU/hr-ft-^oF.

Various methods exist for improving the thermal conductivity of concrete without affecting its strength characteristics. Absorption of moisture increases the thermal conductivity, and a saturated concrete may have a value as high as 2.0 BTU/hr-ft-^oF. Free moisture increases of 1% in weight increase the conductivity by about 5%. Air dried concrete made with sand or gravel as a coarse aggregate has a conductivity slightly greater (~20%) than concrete made with limestone. The conductivity of the coarse aggregates is the most important factor affecting the conductivity of saturated concretes. One example of partially dried concretes made with a high proportion of steel punchings indicated a conductivity range of 1.5 - 2.0 BTU/hr-ft-^{o}F (Reference V-3). For a particular aggregate, thermal conductivity increases with increased weight density of the concrete. Aging seems to have little effect on the conductivity.

C. Earth Heat Exchanger and Earth Heat Storage

The most reliable and readily available form of energy for highway deicing is the natural energy stored near the earth's surface. This form of low temperature energy should not be confused with the earth's internal heat available several thousand feet below the surface. Each cubic foot of ordinary soil has a heat capacity of about 40 BTU that is released if it is cooled $1^{o}F$. The energy extracted by cooling a block of soil, 50 ft. x 50 ft. x 40 ft., $30^{o}F$ would be equivalent to the energy released by burning four tons of coal. Extracting this heat energy from the soil for use in deicing requires an earth heat exchanger. An earth heat exchanger buried in the earth in intimate contact with the soil is needed to transport heat to or from the earth. The temperature differential between the roadway surfaces (in practice, a heat distribution system located a small distance beneath the roadway) and the deep earth provides the driving potential for the heat exchanger. Primary factors of importance are the rate of heat loss (or gain) of the exchanger with time and the temperature change with time. These factors are affected by the thermal properties of the soil.

Soil properties vary from location to location. Early in the study, two soils were chosen--one with a conductivity of 14 BTU/hr-ft^2-^{o}F/inch representing a wet clay and one with a conductivity of 5 BTU/hr-ft^2-^{o}F/inch representing a low conductivity moist soil. System studies were based on a medium conductivity between these two soils.

Kersten at the University of Minnesota has obtained thermal conductivity data from laboratory testing. Figure V-2 presents the variation of thermal conductivity of silts and clay soils with dry density for moisture contents of 10%, 15% and 20%. Figure V-3 presents the variation of dry density versus thermal conductivity for

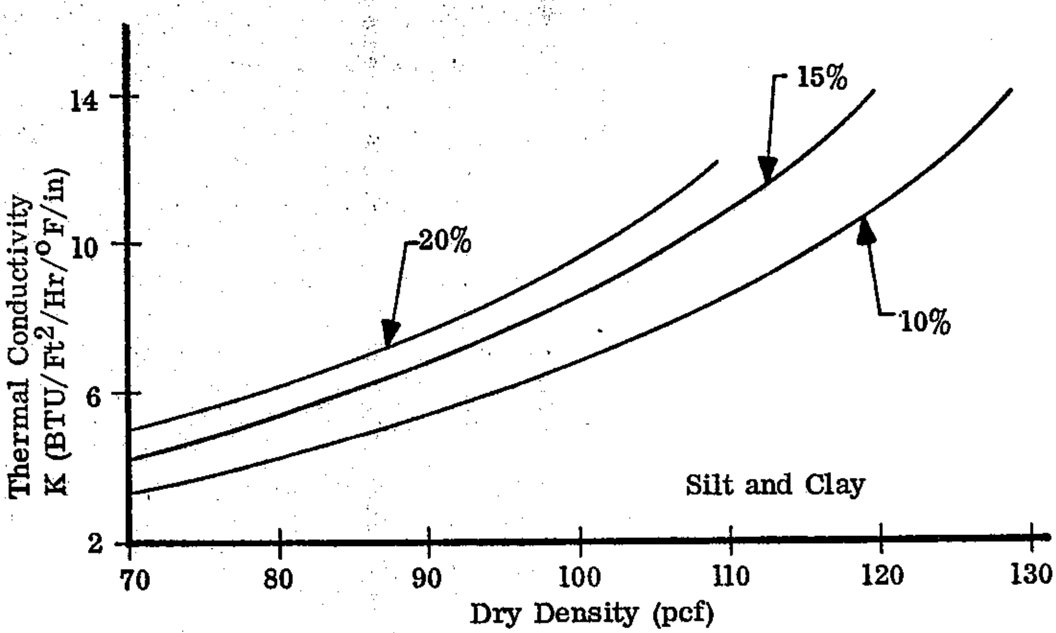


FIGURE V-2: VARIATIONS OF THERMAL CONDUCTIVITY OF SILT & CLAY SOILS WITH DRY DENSITY FOR VARIOUS MOISTURE CONTENTS

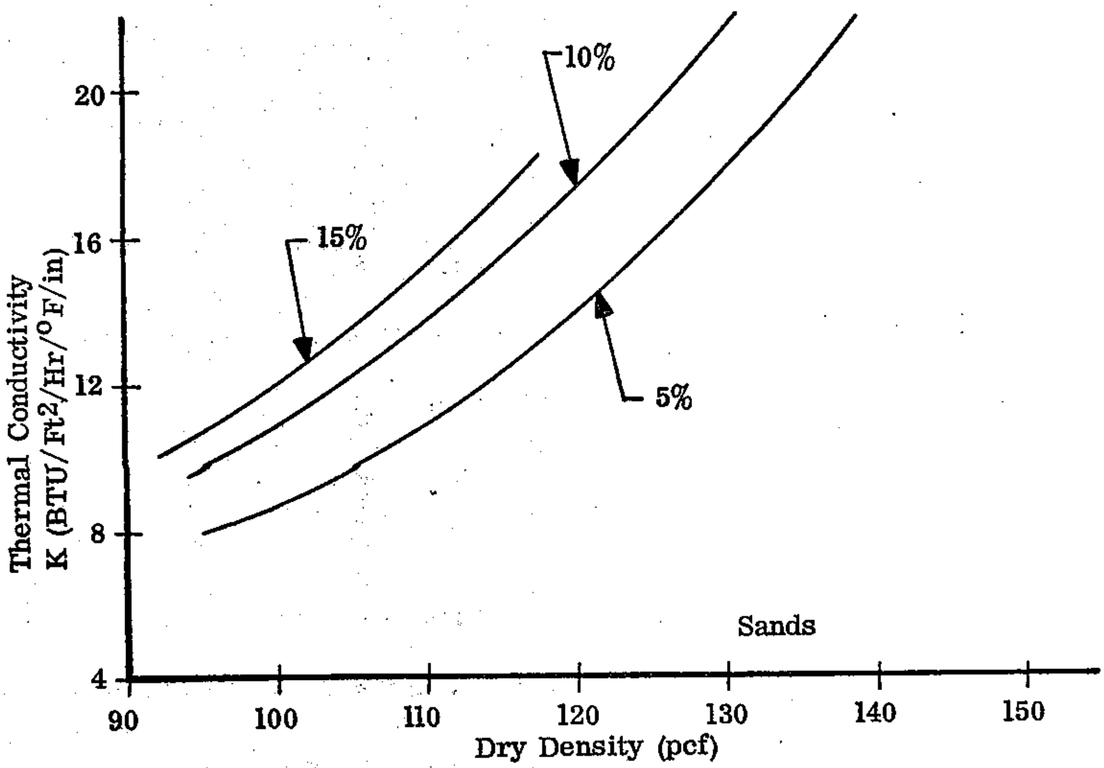


FIGURE V-3: VARIATIONS OF THERMAL CONDUCTIVITY OF SANDS WITH DRY DENSITY FOR VARIOUS MOISTURE CONTENT sandy soils at various moisture contents. As expected, the thermal conductivity increases for increases in density for constant moisture content. For constant density, conductivity increases with increases in moisture content.

This data indicates that a beneficial effect could be obtained by introducing water into the soil as the exchanger system is installed in the soil. The downward flow of water would increase density as well as local moisture content. Both effects would increase the thermal conductivity in the immediate vicinity of the vertical transporter system and therefore permit more heat to be withdrawn from or added to the earth. In addition to the physical properties of the soil, the average annual temperature for a given location is important since this will very closely approximate the driving temperature for a natural earth heat source.

The data in Table V-3 indicate the temperature ranges to be encountered in the states included in this study. Most of the data are from airports near the cities indicated; thus, they should be appropriate for beltway and highway systems near the various population centers. The conditions in the cities themselves will be less severe.

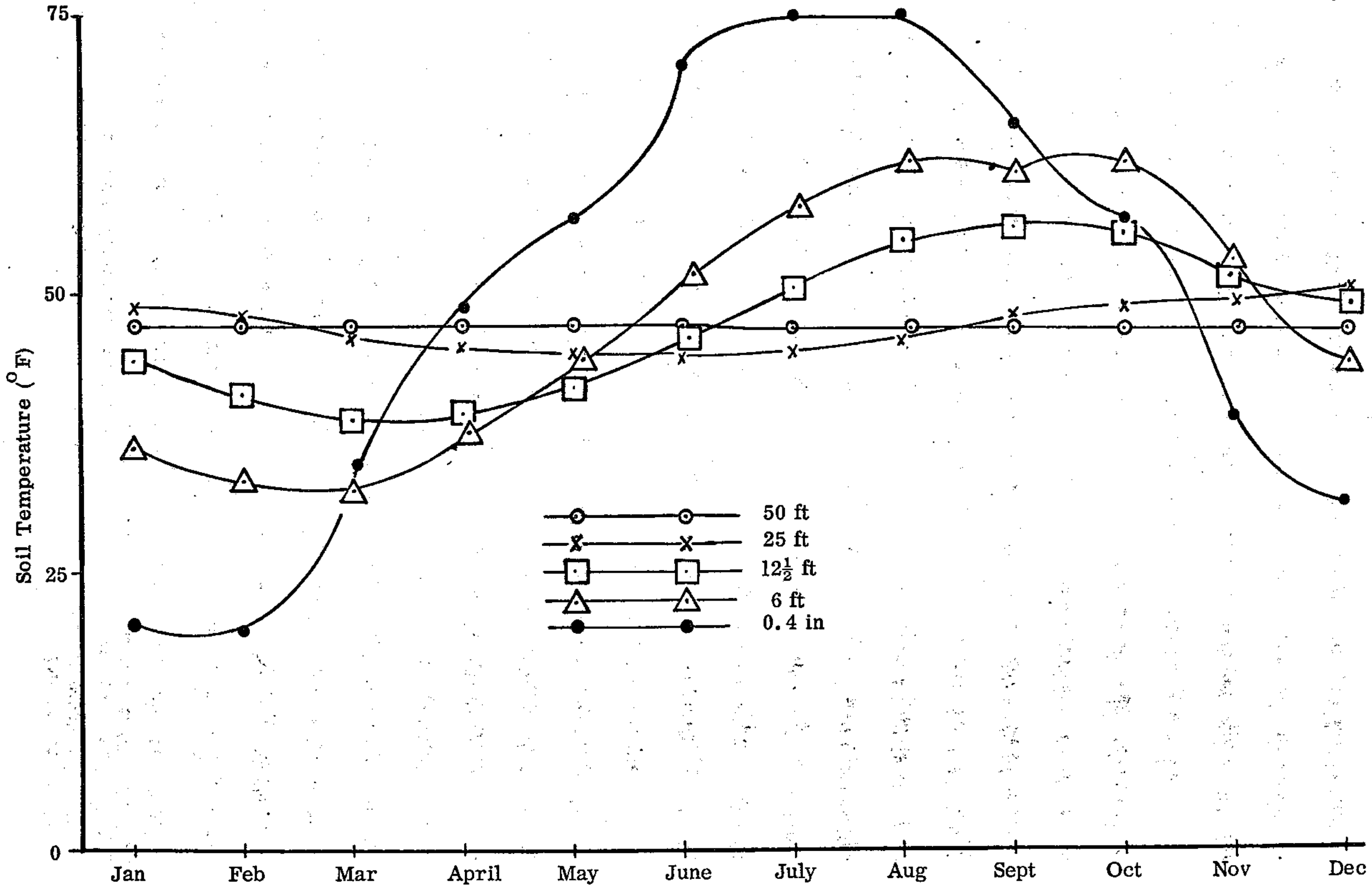
The yearly average temperatures can be utilized in the estimation of the feasibility of utilizing an earth reservoir system. Assuming that the average soil temperatures at depths greater than 15-20 feet approach the yearly average of the surface temperature to within $\pm$ 5°F, we can determine that in the four states being considered nearly every locality will have reservoirs 15 to 25°F above freezing. This is in line with previous general observations (Ref. V-5) and can be inferred from detailed observations made at the University of Minnesota. Figure V-4 indicates soil temperature variation with depth throughout the year. These curves follow the predicted patterns very closely; i.e., at depths over thirty feet the soil temperature approximates the

	Dec. °F	Jan. °F	Feb. °F	Mar °F	Length of Probable Freeze Period (Days)	Yearly Avg. Temp.
Baltimore, Md.	35.8	34.8	35.7	43.1	158	55.2
Wilkes-Barre, Pa.	29.4	27.7	28.3	36.2	159	49.4
Philadelphia, Pa.	33.9	32.3	33.2	41.0	146	53.5
State College, Pa.	30.5	28.7	29.3	36.6	178	50.1
Pittsburgh, Pa.	30.7	28.9	29.2	36.8	183	50.3
Erie, Pa.	30.7	27.3	26.4	33.6	178	48.7
New York (LaGuardia)	36.4	33.6	33.6	40.8	136	54.7
Albany, N. Y.	26.5	22.7	23.3	33.0	230	47.6
Buffalo, N. Y.	25.9	24.5	24.1	31.5	178	46.7
Rochester, N. Y.	26.7	25.2	24.9	32.3	177	48.0
Syracuse, N. Y.	27.8	24.0	24.3	32.6	178	48.0
Worcester, Mass.	27.2	24.0	24.9	32.8	159	46.8
Boston, Mass.	33.3	29.9	30.3	37.7	127	51.4

TABLE V-3

AVERAGE MONTHLY WINTER TEMPERATURES AND
YEARLY AVERAGE TEMPERATURES FOR VARIOUS EASTERN CITIES

FIGURE V-4: SOIL TEMPERATURE (UNIVERSITY OF MINNESOTA) VS. DEPTH



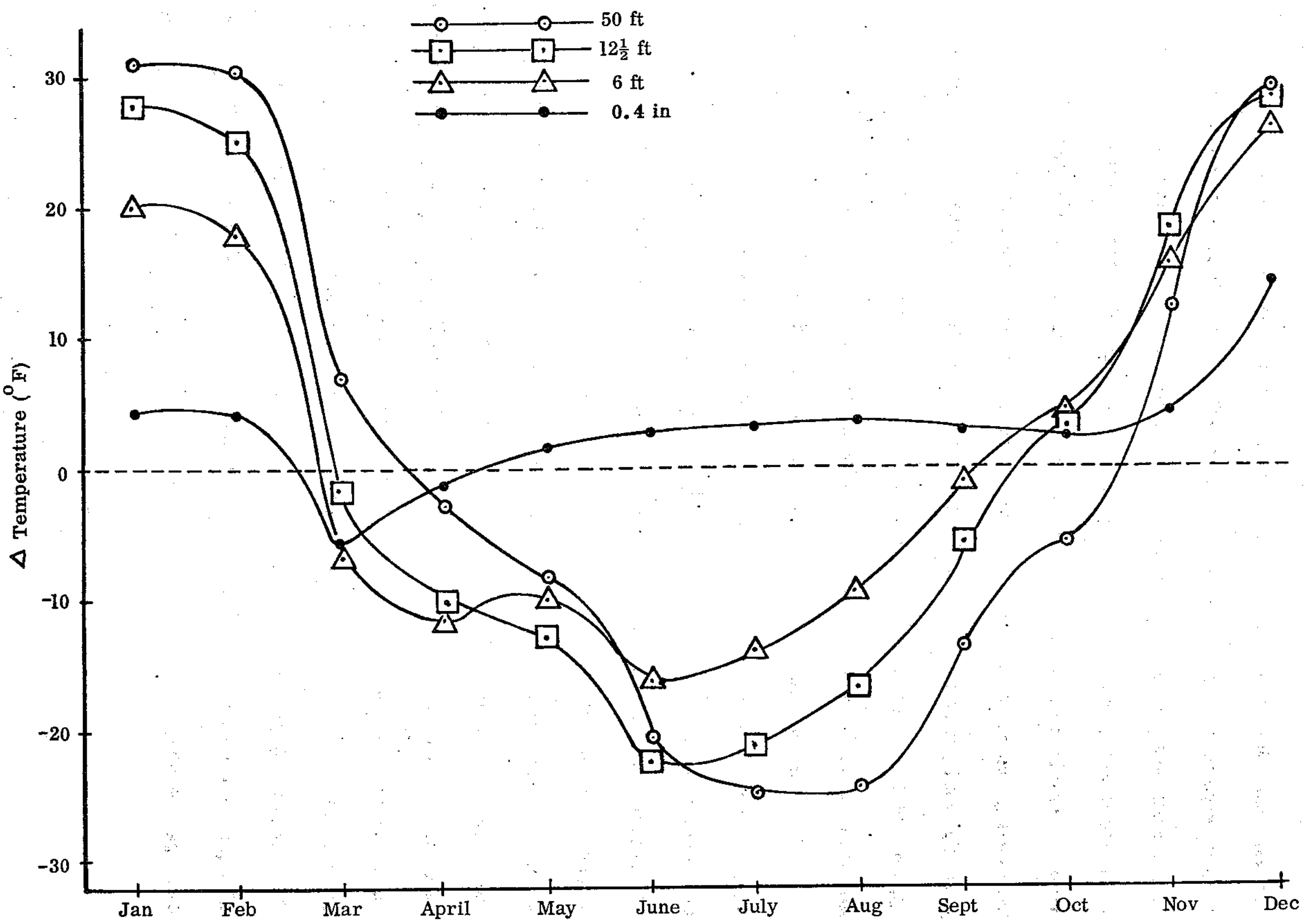
yearly average of the surface temperature, and that large departures from the average value are not experienced much below 15 feet. These conclusions hold well for loam soils and must be modified slightly for sandy, clay, or rocky areas.

Figure V-5 shows the variation between soil and air temperatures for a single year. The month of March averaged eleven degrees warmer than normal, while the other months were fairly close to their normal averages. The sharp changes in the values of ΔT in March indicate that the deep reservoirs in the earth follow the long term temperature trends rather than short fluctuations during one year. It should also be noted that at depths of 25 to 50 feet the yearly temperature fluctuations are $\pm 2^{\circ}F$ or less, while near the surface the monthly fluctuation is as much as $\pm 10^{\circ}F$ and the yearly fluctuation is as great as $70^{\circ}F$. Thus, the 20 to 50 foot level holds great promise as a stable reservoir for heat, especially if a simple method of pumping some of the excess summer heat down to this level can be developed.

Aside from being a potential heat source, the earth represents a practical energy storage reservoir for other primary heat sources. In the case of nuclear waste as the primary source, it is desirable to utilize all of the power produced over the entire year during the short intervals associated with snow melting and deicing. The available thermal energy can be stored as sensible heat in an earth reservoir. The earth's relatively high heat capacity permits the required energy to be stored in reasonable volumes of earth while still maintaining the storage reservoir temperature below $90^{\circ}F$ (low temperature heat source). On the other hand, the low thermal diffusivity of earth ($\alpha \approx 0.02$ ft^2/hr for average soil) results in low energy losses and therefore high storage efficiencies* for the storage volumes and temperatures that

* The storage efficiency is defined as the ratio of the energy required for melting to the sum of the energy required for melting plus the energy lost to the soil surrounding the reservoir.

FIGURE V-5: EXCESS OF SOIL TEMPERATURE OVER AIR TEMPERATURE (UNIV. OF MINN. 1968)



are required. Storage efficiencies of approximately 75% are readily obtained for earth storage reservoirs. Assuming a storage efficiency of 50%, twice as much energy must be supplied to the storage reservoir as would be dissipated at the roadway surface during periods of snow melting and deicing. However, in terms of a nuclear waste heat source which is dissipating power continuously, although the total energy requirement is increased by storage, when averaged over the entire year, the total power requirement and therefore the nuclear inventory is reduced by approximately a factor of five. Thus, approximately five times as many nuclear installations can be obtained if an earth storage reservoir is employed.

The available thermal energy could also be stored as the heat associated with a phase change in a fluid. The heat of phase change is interesting because a large amount of heat can be stored (at constant temperature) in relatively small volumes. The heat of fusion is particularly interesting since freezing/melting is essentially a constant volume process. The phase change must occur at a temperature sufficiently above $32^{o}F$ in order to make the resulting heat liberated usable for deicing. Water therefore would not be suitable. This method of storage would be more efficient than earth storage because the energy could be stored in smaller volumes of fusible material and at lower temperatures. The combination of smaller volumes and/or lower temperatures results in lower storage and transport losses. If a storage reservoir is employed, the cost of the fusible material as well as its containment must be compared to the cost of higher power requirements and greater transport lengths in determining which method of storage is best.

D. Heat Pipes as Applied to Earth Heat Exchangers and Isothermalization of Roadway Surfaces

The problem of earth heat exchanger development has been greatly improved in recent years with the advent of a novel heat transfer technology known as the heat pipe. A heat pipe is an isothermal device which is capable of transporting heat between two locations in a completely static manner. Technically, it can be described as a closed system containing a fluid in two-phase equilibrium. It consists of an evaporator, a condenser, and a capillary structure to provide pumping power. Heat is transported in the form of latent heat of evaporation, and capillary and/or gravity forces are utilized to recirculate the condensate. When integrated with an energy source heat pipes can provide a redundant heat transport system having a high probability against failure. The isothermality of a heat pipe permits realization of the maximum potential of an earth storage system.

Tests have been performed by Dynatherm Corporation to establish the feasibility of using heat pipes to transport energy from a storage reservoir to a roadway surface. A 12' x 3/4" O.D. heat pipe using ammonia as the working fluid was installed vertically to a depth of 10 feet, as shown in Figure V-6. The pipe has thermocouples located along its length to provide temperature data. The part of the pipe buried in the ground represents the evaporator (heat input) section, while the part above the ground surface is the condenser section where heat is dissipated. An ordinary pipe was installed alongside the heat pipe for comparative purposes.

Data for the heat pipe indicated that it was completely isothermal over its entire length during its operation. A comparison between the heat pipe and the dummy pipe is presented in Figure V-7. Whereas the dummy pipe's temperature dropped below

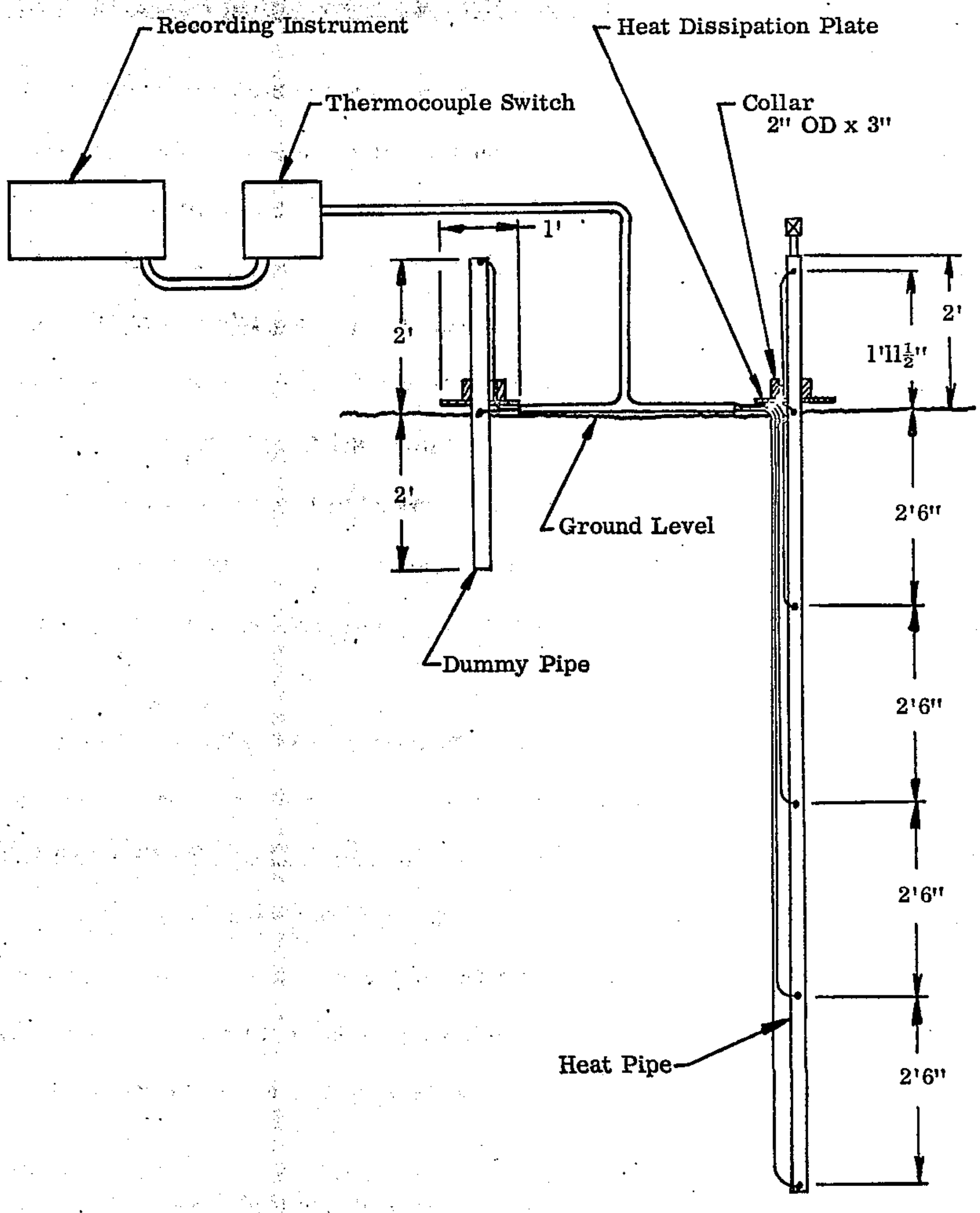
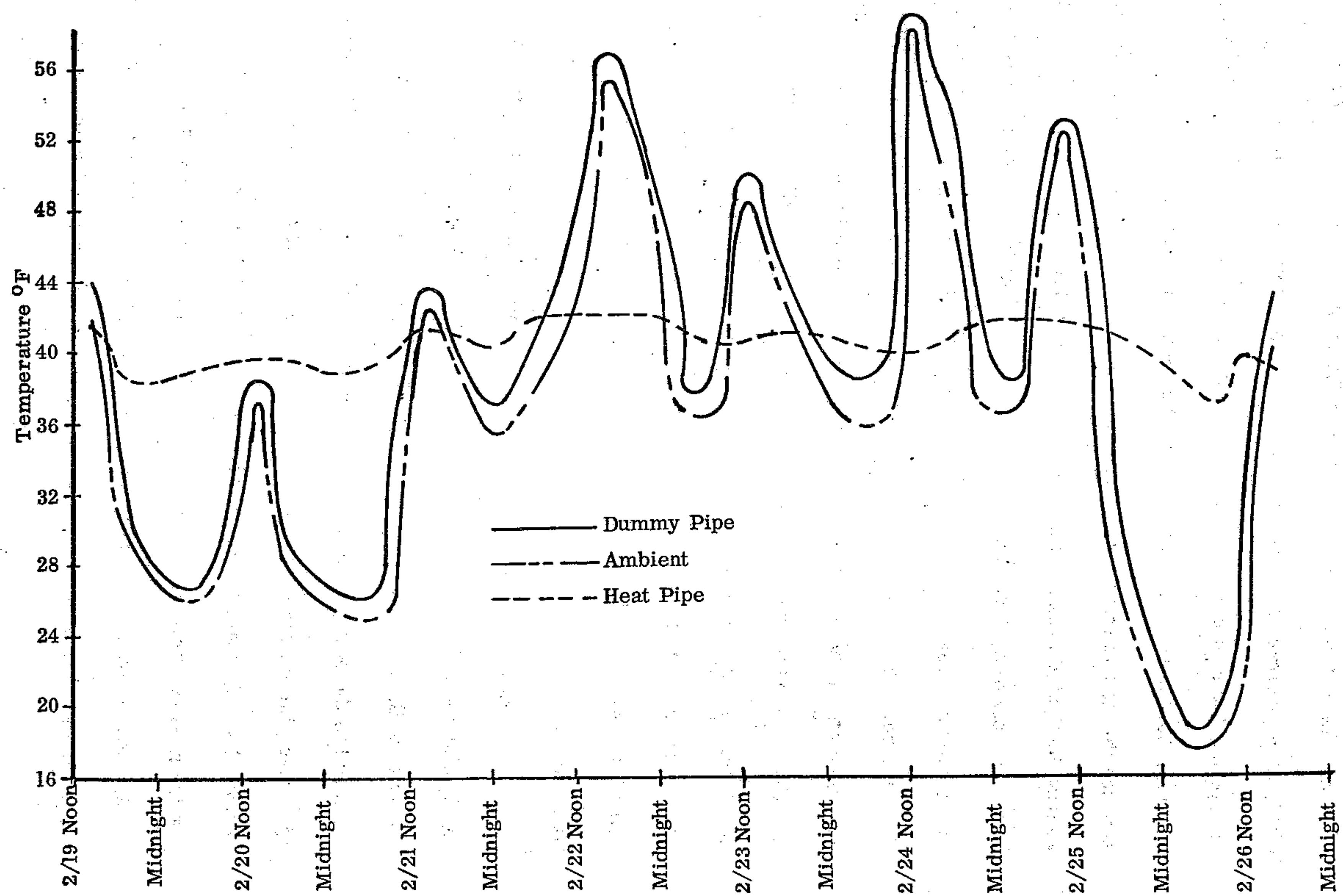


FIGURE V-6

EARTH-HEAT PIPE HEAT TRANSPORT EXPERIMENT

FIGURE V-7: COMPARISON OF HEAT PIPE TEMPERATURE WITH AMBIENT TEMPERATURE



freezing, the heat pipe operated isothermally at about 38°F during periods of heat dissipation (subfreezing temperatures). On warm days, when no heat was being dissipated, the heat pipe assumed the temperature of the soil at the 10' depth (~43°F). The fact that the heat pipe was operating at temperatures above the ambient is a demonstration that it was transporting heat from the earth. However, the magnitude of the energy dissipated is not readily determined from this type of test.

Calorimetry tests were performed which consisted of melting a known amount of ice over a period of time in order to determine the amount of energy being extracted from the soil. The tests consisted of placing a 2' long x 10" O.D. cannister around the heat pipe and filling it with water at 32°F and then inserting a known amount of ice. An identical cannister was placed nearby for comparison. Melting rates of approximately 0.5 lb/hr, corresponding to ~ 75 Btu/hr, were experienced for the heat pipe system. This is equivalent to melting 1" of snow on a 1 ft^2 surface per hour. This result correlates well with the theory describing the performance of earth heat exchangers (Reference V-4).

In addition to the calorimetry tests, an actual snow melting test was performed. A 12" aluminum disc, 1/4" thick, was clamped to the upper portion of the heat pipe. The purpose of the disc was to provide a heat dissipation surface to melt snow. The disc was clamped to the heat pipe on the evening of March 17. A similar disc attached to a dummy pipe was placed nearby for comparison. The following morning there was a moderate snowfall which lasted for about 2 hours. Approximately one inch of snow had accumulated on the ground within that time. The results of the test are shown in Figures V-8 and V-9. Absolutely no snow had accumulated on the heat pipe system, while approximately 1/2" of snow had accumulated on the dummy plate at the end of the snowfall. The snow

FIGURE V-8. HEAT PIPE EXPERIMENT
ONE-HALF HOUR AFTER START OF SNOWFALL

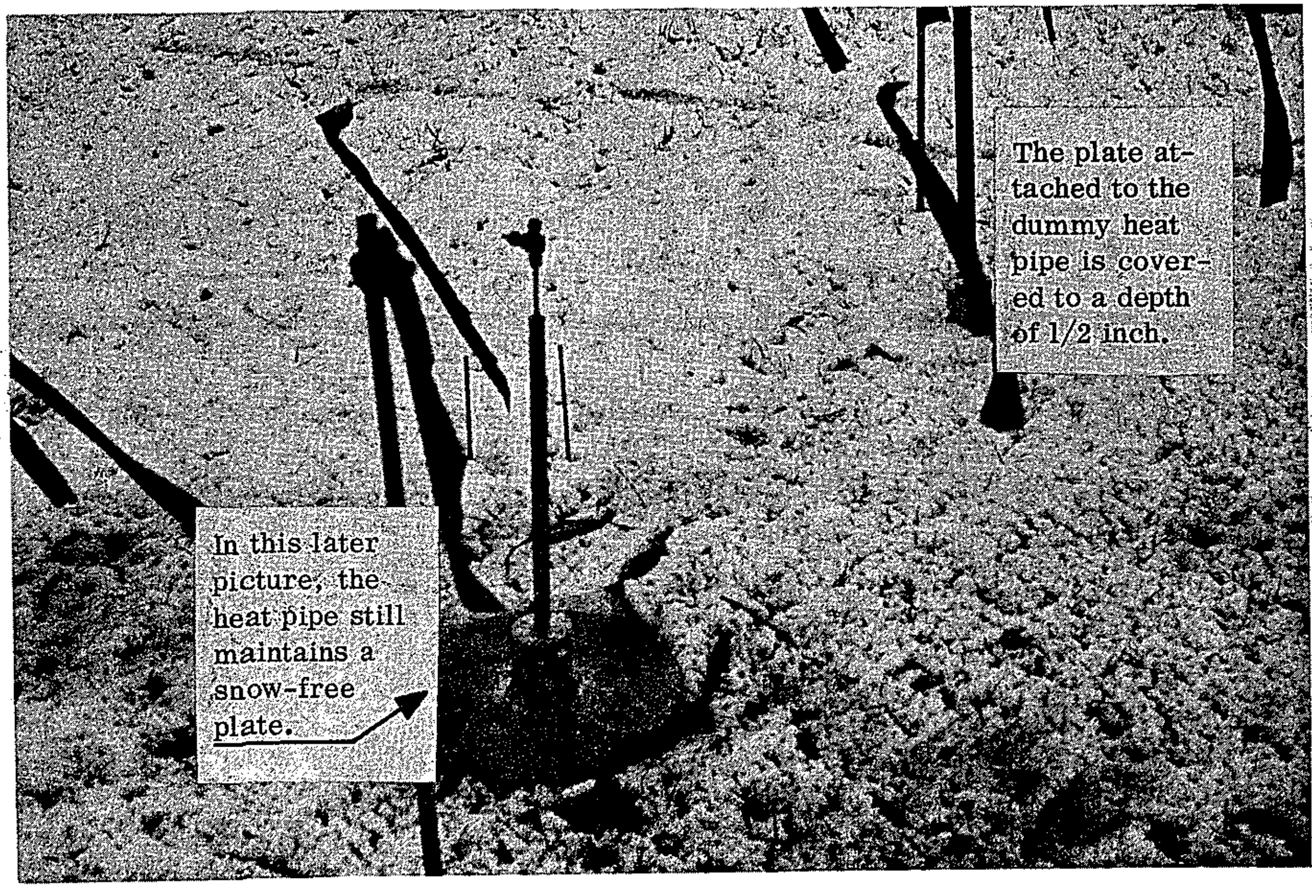


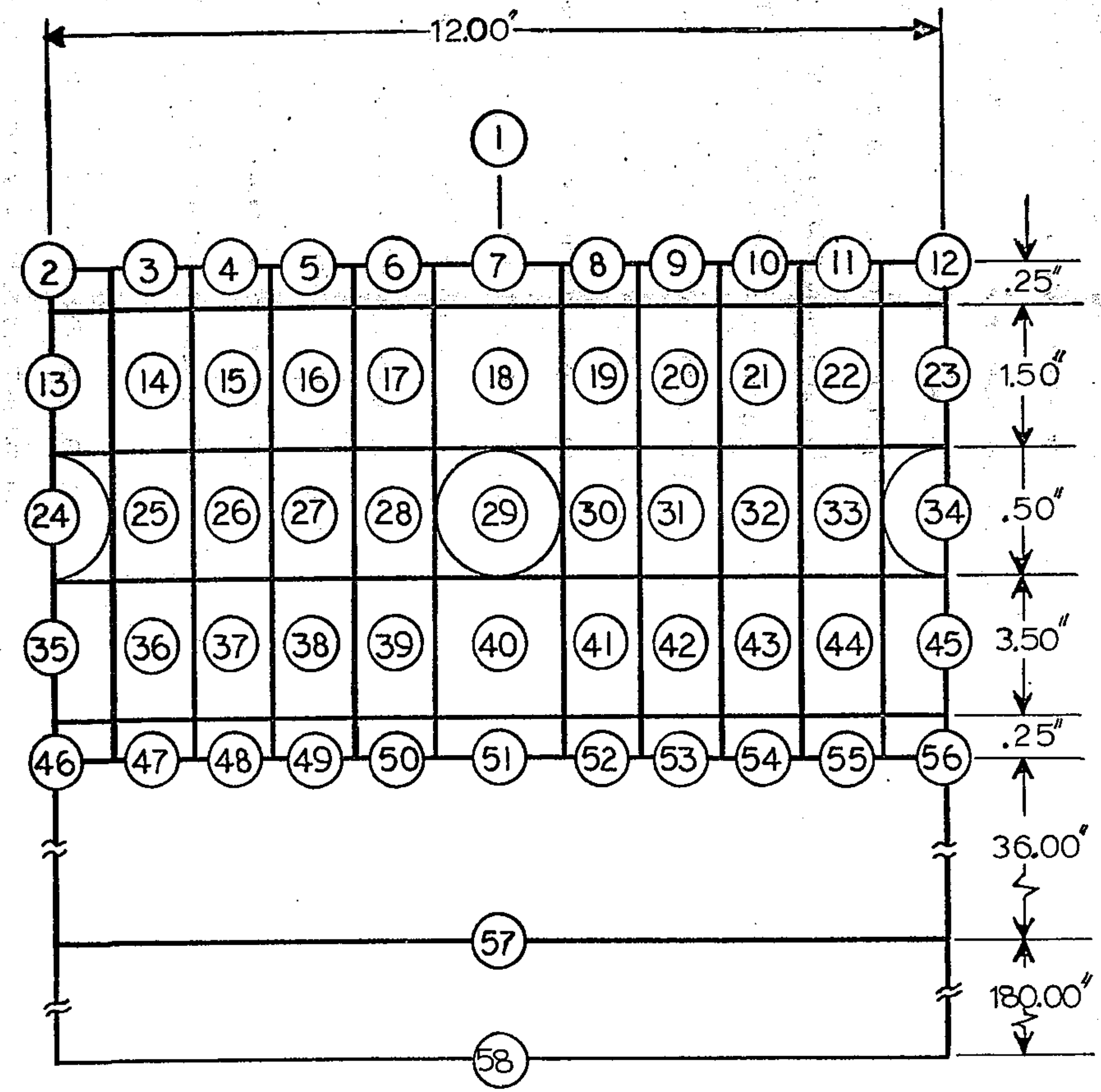
FIGURE V-9. HEAT PIPE EXPERIMENT
TWO HOURS AFTER START OF SNOWFALL

was observed to melt almost instantaneously upon striking the heat piped-heat dissipation surface. The rate of heat dissipation corresponds to 35-40 Btu/hr. The rate of heat transfer obtained with the rather low driving temperature potential is more than adequate for the prevention of preferential freezing. It can also be concluded that, at least in moderate climates, a natural earth reservoir-heat pipe transport system can provide sufficient energy for snow melting and deicing. Such a system requires roadway materials of relatively high conductivity ($k > 1.0$ Btu/hr-ft-$^{\circ}$F), an isothermal heat distribution mat, along with isolation of the individual transport heat pipes in the ground. In this way, the maximum driving potential of earth as a heat source can be realized.

Except for potential systems employing radiant energy, a thermal grid is an essential component in any system where heating is used to accomplish deicing. The grid is necessary to distribute the heat within the roadway pavement so that relatively uniform heat dissipation occurs at the roadway's surface. Typically, this grid has consisted of shielded electrical heating elements, electrical wire networks, or pipes with pumped fluid as the heating medium. A heat pipe mat could also be used as a thermal grid. The heat pipe mat would provide passive isothermalization (and therefore uniform heat distribution) as well as serving as a structural reinforcement for the pavement. It also has the advantage that it can be integrated with any of the potential energy sources being investigated.

Regardless of what type of thermal grid is used, the analysis of the grid's performance is identical. A two-dimensional thermal model has been developed to analyze the performance of the thermal grid. This model is shown in Figure V-10. Nodes 24, 29, and 34 represent the heating elements of the grid; node 1 is the ambient air; nodes 57 and 58 are the ground; and the remaining nodes are the pavement. Deep

FIGURE V-10: THERMAL MODEL OF ROADWAY HEAT DISTRIBUTION SYSTEM



ground (node 58) and ambient air (node 1) temperatures were fixed at 45 and 20^{o}F, respectively. Conductance values typical of heat pipes were used for the heating elements. The heat transfer coefficient was determined such that 25 W/ft^2 would be dissipated by the roadway surface at 34^{o}F to the ambient air. In this way, melting would be guaranteed. The centerline of the heating elements was located two inches below the surface of the roadway. Thermal conductivity of the pavement material below the center of these elements was fixed at 0.5 Btu/hr-ft -^{o}F. The model has been programmed, and a steady-state thermal analysis was performed using "NETHAN III" Thermal Analyzer Program.

Heat flux and temperature distributions were determined for various values of the thermal conductivity of the pavement material above the heating elements and also two different spacings of these elements. The heat input from the heating elements that must be supplied in order to guarantee a minimum of 25 W/ft^2 at the surface was also determined. Results of the analysis are summarized in Table V-4. A typical resultant heat flux and temperature distribution is shown in Figure V-11 for Case #3.

TABLE V-4

SUMMARY OF THERMAL ANALYSIS OF HEAT DISTRIBUTION MAT

Case No.	Heat Element Spacing (in)	Thermal Conductivity of Pavement (Btu/hr-ft-^{o}F)	Heat Input (W/ft^2 of Roadway	Temperature of Heat Elements (^{o}F)	Roadway Surface Heat Flux (Max) (W/ft^2 of Roadway)
1	6	0.5	30	112	35.9
2	6	1.0	28	72	32.1
3	6	2.0	27	54	30.0
4	4	0.5	28	82	28.7
5	4	2.0	25.2	46	25.4

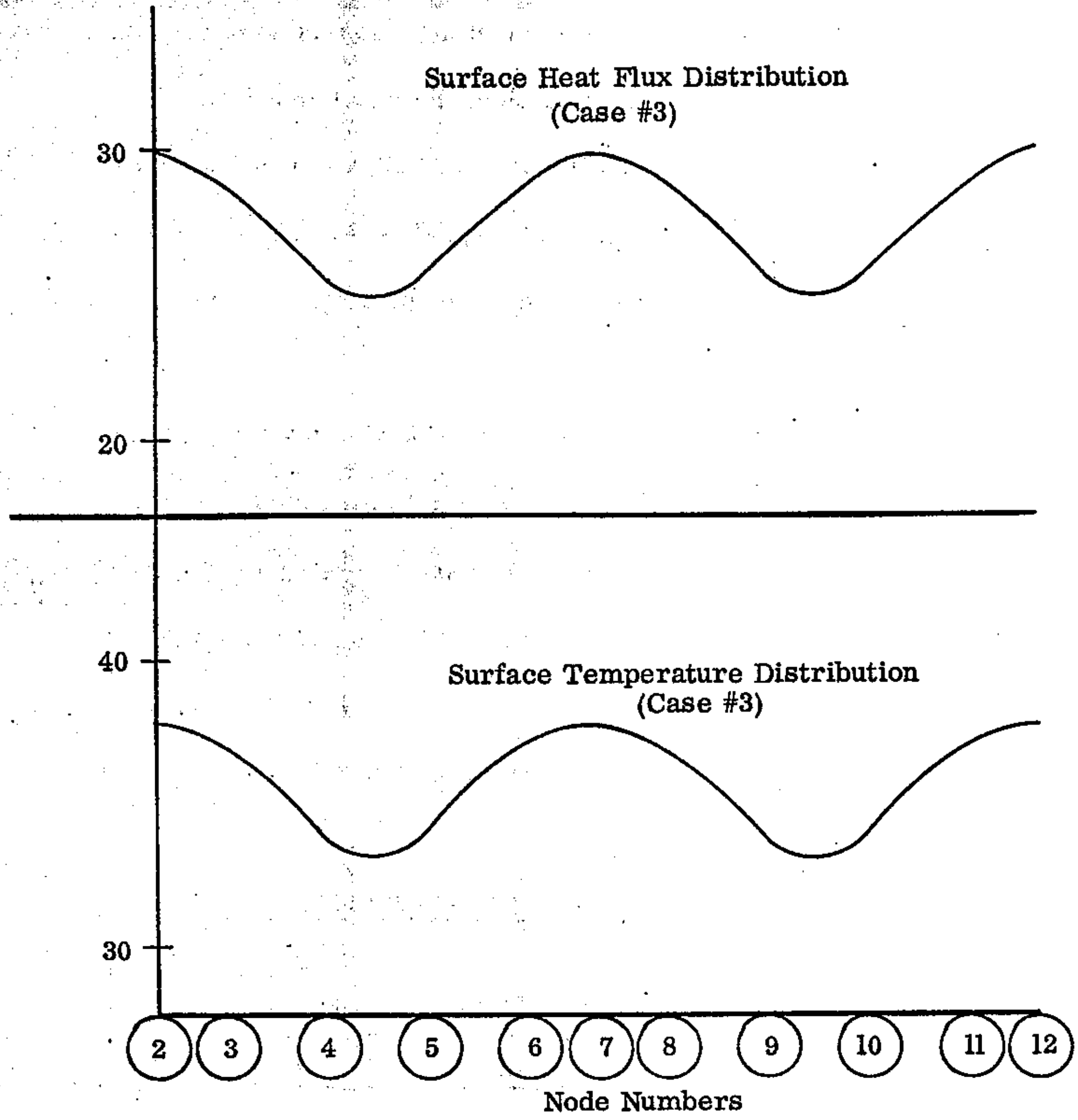


FIGURE V-11: ROADWAY SURFACE
HEAT FLUX AND TEMPERATURE DISTRIBUTION

As indicated in Table V-4, an element spacing of four (4) inches and a thermal conductivity of 2 Btu/hr-ft-^{o}F is required to get an essentially uniform heat distribution. While this combination of spacing and thermal conductivity gives approximately 100% efficiency in terms of heat flux distribution, the temperature of the heating elements is approximately 5^{o}F higher than for a continuous planar heat distribution grid. Consequently, as regards an earth storage system, the maximum temperature driving potential could not be realized unless there is a closer spacing of the heating elements in the grid. Increased operating costs associated with higher transport and/or storage losses for increased temperature potentials must be compared with increased installation costs associated with closer element spacings required to realize maximum temperature potential in order to arrive at an optimum heat distribution system.

As discussed previously, conventional air-dried concretes have a thermal conductivity of 0.75 Btu/hr-ft-^{o}F. However, the conductivity can be increased to as high as 2 Btu/hr-ft-^{o}F when saturated with water. This could very well be the case when melting is occurring at the roadway's surface. Also, Wirand concrete is being developed which has a thermal conductivity of 1.0--better than twice the strength of conventional roadway materials--and excellent wear resistance. Thus it is quite possible to reduce the depth of pavement above the elements to approximately one inch, in which case the thermal performance of the grid would be essentially the same as for Case #5. With a heat distribution system operating at or below 46^{o}F a natural earth reservoir-heat pipe transport system is feasible. The practicality of such a system in terms of design and installation costs remains to be determined.

A parametric analysis has been performed to provide design data for an earth energy storage-heat pipe transport system. A conceptual design for this system is presented in Figure V-12. The following assumptions were made in performing the analysis:

1. Planar-isothermal heat distribution mat located at a depth (d) below the pavement surface - no distribution losses.

2. Uniform ground temperature - no transport losses.

3. Isolated transport heat pipes - this is accomplished by staggering the heat pipes as shown in Figure V-12.

4. No interface loss between the transport pipes and heat distribution mat.

5. Average soil conditions - heat transfer rate from ground to transport pipes is W = 4 Btu/hr-ft^2-^{o}F.

6. Length of pipe in pavement (ℓ) is 12 feet.

7. Outside diameter of transport pipes is one inch.

Under these assumptions, the total temperature drop between the ground and the pavement surface is given by

$$T_s - T_p = \Delta T_p + \Delta T_{hp} + \Delta T_g \qquad \text{(V-6)}$$

where T_s = Temperature of the earth energy storage system

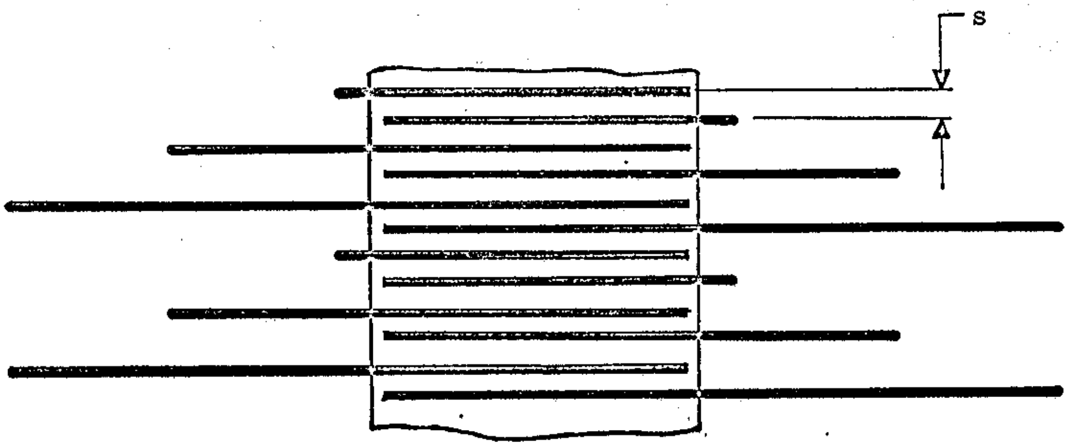
T_p = Temperature of the roadway surface

ΔT_g = Temperature drop between the earth reservoir and the transport heat pipes

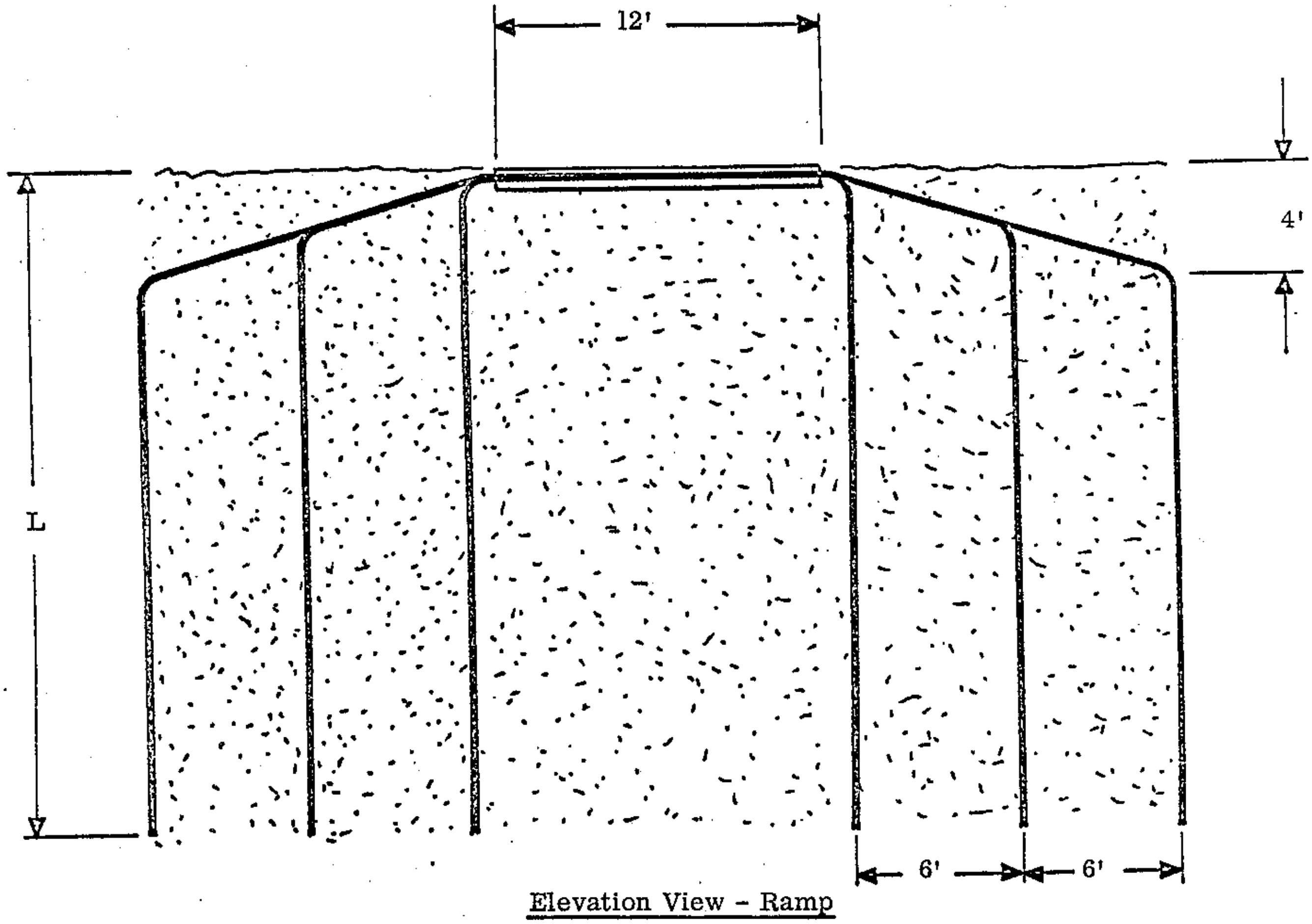
ΔT_{hp} = Temperature drop through the heat pipe

ΔT_p = Temperature drop through the pavement from the heat distribution mat to the surface of the roadway

With these temperature drops taken into account, the following expression exists which relates the heating requirements and temperature driving potential to design parameters of the system.



Plan View - Ramp



Elevation View - Ramp

FIGURE V-12

CONCEPTUAL DESIGN - RAMP HEATING SYSTEM

$$\frac{T_s - T_p}{q} = 0.284\ \frac{d}{k} + 39.2\ \frac{s}{L} \qquad \text{(V-7)}$$

where
- d = Depth of heat distribution mat below the roadway (in.)
- k = Thermal conductivity of roadway material above the mat (Btu/hr-ft-^{o}F)
- L = Length of transport pipe in the ground (ft)
- s = Spacing of transport pipes
- q = Heat flux dissipated at the surface (w/ft^2)

This relation has been solved for a range of practical values of the design parameters. The results are shown in Figure V-13. As an example of the use of this Figure consider the design of a natural earth energy source ($T_s \approx 55^{o}F$) in an area where heating requirements are 25 W/ft^2. In order to have melting $T_p \approx 33^{o}F$, thus

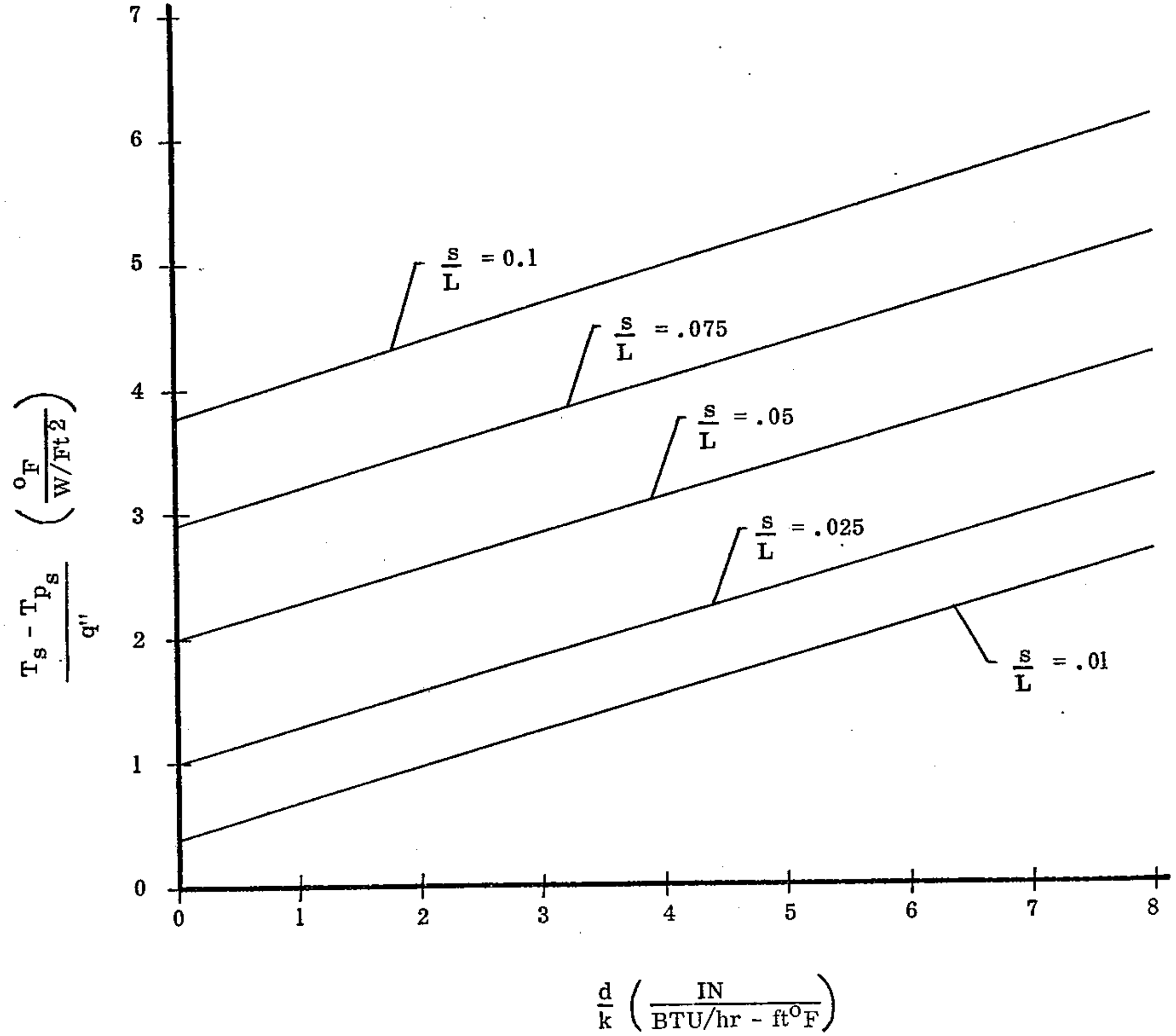
$$\frac{T_s - T_p}{q} = 0.88\ \frac{^{o}F}{w/ft^2}$$

Therefore, for a value of $d/k = 1$ (e.g., d = 1 inch, k = 1.0 Btu/hr-ft-^{o}F) a value of approximately .015 is required for s/L.

Thus if the transport pipes are spaced at one foot intervals (s = 1'), they will have to run approximately 75 feet deep into the ground. Cost factors associated with spacing (s) and depth into the ground (L) (e.g., deeper holes vs. fewer holes, etc.) will have to be accounted for in a cost model when determining an optimum system design. While the length of transport pipe may seem quite large, a vertical heat pipe acting essentially as a refluxer will experience no difficulty in pumping the required heat through these distances. The use of nuclear waste heat in combination with an earth storage reservoir-heat pipe transport system would of course increase the

FIGURE V-13

PARAMETRIC DESIGN OF EARTH STORAGE - HEAT PIPE TRANSPORT SYSTEM



T_s = Source Temperature

T_{p_s} = Pavement Surface Temperature

q'' = Heat Flux

d = Depth of Isothermal Grid Below the Surface

k = Thermal Conductivity of Pavement

L = Length of Transport Pipes in Ground

s = Spacing of Transport Pipes Beneath Roadway Surface temperature of the storage system. Provided that sufficient energy is stored at temperatures not substantially greater than for natural earth (no significant transport losses) the use of nuclear waste could substantially reduce the required length of transport pipe. In this case, the cost of installation and containment of a nuclear waste heat source must be compared to installation costs for the additional length of transport pipe required if only natural earth heat is used.

E. Technology of Hole Drilling

Vertical transport pipes must be installed in the earth to a depth of 30 to 60 feet quickly and cheaply. Consideration must be given to driving or pushing the pipe as well as placing them into drilled holes. Assuming transporter pipes made of conventional pipe steel and charged with the working fluid in advance of installation, driving the pipe, as one would a pile, may not be feasible because of possible damage. In very soft, loose silts and sands a jetting process would be beneficial for either a pushing or driving method. In consideration of driving or pushing versus drilling, one must ascertain the resistance to penetration. For a stiff clay with a maximum unconfined compressive strength ranging from one ton/ft^2 to two ton/ft^2, a one-inch diameter transporter pipe embedded a depth of 30 feet would develop a maximum resistance approximately ranging from 4.3 tons to 8.6 tons. A medium dense sand having a weight density of 120 pcf and an angle of internal friction of 30 degrees penetrating a depth of 30 feet would develop a resistance of approximately 4.5 tons. The above estimates include not only lateral resistance but also 10 percent for tip effects. The above vertical load requirements are feasible from an equipment point of view using hydraulic jacks or continuously driven friction rolls. Because of the large lengths of pipes to be handled (embedded depth plus horizontal travel) of approximately 50-60 feet or more, a vertical boom or equivalent would be necessary. Downward thrust could be applied thru a mechanism gripping the circumference of the pipe. Other techniques such as the utilization of a giant impact hammer device whereby the pipes are shot into the ground (such as has been used in installing steel bars into rock for military construction) should be studied.

Until more definite information regarding the future needs for mass installations is available and the feasibility of developing special equipment is investigated, presently available drilling techniques must be considered. The most economical method, and thus the only one under consideration, is the power auger technique using a hollow stem auger with the transporter pipe advanced down the hollow stem to the desired depth, at which time the hollow stem auger is withdrawn leaving the soil in intimate contact with the transporter pipe. On a prototype basis the cost of the hollow stem procedure would be approximately $1.00 per foot of depth. Development of special equipment for transporter pipe installation would probably reduce the costs to perhaps 20¢ per foot of depth. Advancing down the center of a hollow stem would have advantages over pre-drilled holes; for example, in silts and sands a pre-drilled hole would probably cave in.

Additional development studies are strongly advised in this area of installation equipment and procedures.

F. Practices and Technology of Concrete Pavements

Numerous aspects of current practices and technology in the field of concrete pavements are important in pavement deicing considerations. These include pavement life, thermal properties of concrete, structural thermal effects, metal-concrete compatibility, slab reinforcement requirements, interchange geometry, construction side forms, haul or work road use, underdrains, sawed joints, concrete placement, etc.

1. Pavement Life

Bureau of Public Roads studies of highway life through the U. S. was reported by Gronberg and Blosser (Reference V-6) giving average pavement lives of various paving types for the years between 1905 and 1952. Table V-5 depicts the results for eight types of pavements. Of primary interest herein are the bituminous concrete roads consisting of one inch or greater thickness meeting precise specifications and rigid pavements of portland-cement concrete with or without a bituminous wearing surface less than one inch. Probably because of heavier axle loads in current use the service life of nearly all pavements decreased from 1905 to 1952. Rigid pavements have average service lives of 20 to 25 years while bituminous concrete is approximately 17 years. Note however that concrete pavements resurfaced with 2 inches of bituminous mat would not be classified as rigid by the above definitions.

Associated with concrete pavement life are various types of distress that generally can be traced to two main causes--deterioration or deficiency of the pavement itself, and that resulting from improper dowel alignment, warping stresses and contraction as well as expansion effects. Deterioration of the pavement itself may be brought about by freezing and thawing (thermal

TABLE V-5

WEIGHTED PROBABLE AVERAGE SERVICE LIFE OF DIFFERENT PAVEMENTS AND PERIODS (GRONBERG AND BLASSER 1956)

Construction Period	Soil	Gravel or Stone	Bituminous Surface Treatment	Mixed Bituminous	Bituminous Penetration	Bituminous Concrete	Rigid	Brick or Block
1905		15.6	34.1		26.4	23.5		40.0
1906-1910	10.5	9.2	38.8		24.7	27.8	41.3	25.1
1911-1915	5.6	15.3	19.5	16.4	24.7	21.8	18.4	21.0
1916-1920	12.7	11.5	19.0	18.4	17.9	19.8	23.3	20.7
1921-1925	9.1	10.1	19.1	14.2	19.0	20.3	27.0	19.6
1926-1930	6.0	8.8	16.1	12.5	18.5	17.8	26.6	20.5
1931-1935	4.0	7.5	11.7	13.3	18.8	16.4	25.7	16.8
1936-1940	3.2	5.6	12.0	14.7	19.6	16.1	23.1	15.6
1941-1945	2.3	5.6	11.1	12.2	15.4	14.1*	21.1*	10.5*
1946-1950	1.5	3.1	9.5	11.7*	12.0*	16.8*	24.0*	
1951-1952	2.1	2.8	9.3*	13.0*	14.7*	17.5*	24.3*	
Average	5.2	8.3	12.6	13.1	18.0	16.8	25.5	19.9

*From Projection Trends

fatigue), use of nondurable materials, alkali-aggregate reaction, scaling resulting from use of salts for ice removal, etc. Thermal deicing methods would eliminate the latter salt deterioration. The general form of distress, due to improperly aligned or "frozen" (poorly lubricated) dowel bars, that prevents freedom of expansion and contraction of the slab is a spalling or cracking of the concrete. Longitudinal cracks and spalling along these cracks may occur due to warping stress. Much of the above distress could be minimized with proper maintenance and care in construction.

2. Thermal Conductivity

Thermal conductivity of the roadway concrete is a major factor in the design of low temperature deicing systems, such as those involving earth heat storage, since the efficiency of such systems increases with higher concrete conductivity. A typical value of thermal conductivity of concrete, air dried in the atmosphere, is approximately 12 BTU/Hr-Ft^2-^{o}F per inch. Absorption of moisture increases the effective thermal conductivity, and a saturated concrete may have a value as high as 24 BTU/Hr-Ft^2-^{o}F per inch. Each one percent increase in free moisture by weight increases conductivity by approximately 5 percent. This is significant because, during the deicing process, melt water will improve the effective conductivity above the value for dried conditions.

Generally, conductivity increases with increased weight density of the concrete; however, the moisture conditions are important. For example, in saturated concretes, the conductivity of the aggregate is the major factor determining the overall effective conductivity of the resulting concrete. In partially dried concretes, the gain in conductivity may be balanced by loss due to decrease in moisture content corresponding to the change from a saturated to partially dried condition. One example of this is a partially dried concrete made with a high proportion of steel punchings resulting in a conductivity ranging from 19 to 25 BTU/Hr-Ft^2-^{o}F per inch, while a saturated concrete made with more conventional aggregate had as high or higher values of conductivity. This seems to be the influence of moisture content.

In an air dried concrete, with limestone as a coarse aggregate, conductivity has been found to be as much as 20 percent lower than concrete made with sand and gravel. All other things being equal, age of concrete alone does not seem to affect conductivity appreciably.

In general, the thermal conductivity of concrete is low and attempts to increase it by additives is not very encouraging. Perhaps this is due to the non-continuous network of aggregates, each surrounded by a continuous matrix of low conductivity cement paste. Research should be conducted on ways to improve thermal conductivity since it is of major importance to deicing efficiency.

3. Metal-Concrete Compatibility

Materials used for the heat pipes and the horizontal heat distribution system must be compatible with the concrete and steel reinforcement. One practical aspect of metal-concrete compatibility of importance is the galvanic action between aluminum and reinforcing steel as well as aluminum-alkali effects. Both of these cause corrosion that may lead to concrete deterioration such as cracking and spalling. These detrimental effects override the commercial and heat pipe advantages of aluminum and point to consideration of steel heat pipes in the heat distribution mat.

4. Slab Reinforcement and Thermal Effects

Thermal effects on concrete pavements have an important influence on their structural capacity and on the reinforcement requirements for highway slabs; hence, an important effect on the economy of deicing systems.

Experimental data indicates strength loss for concrete specimens to be much greater for thermal cycling than for constant exposure to high temperatures; however, the range of temperature differential of 20°F anticipated at deicing time is negligible compared to normal climatic variations. Thus, thermal fatigue due to low temperature deicing systems is considered negligible.

The low conductivity of concrete requires that a heat pipe bar mat be located near the upper slab surface, approximately 1.5 inches from the surface, in order to meet surface heat requirements. To provide uniform deicing the horizontal spacing will be approximately twice the vertical concrete cover. For economy, the heat pipe bar mat should also serve as the slab reinforcement with realistic amounts of steel per unit area of slab. In addition, the inside and outside pipe diameters must provide an acceptable thermal unit with the working fluid in the pipes. Consideration should also be directed to warping stresses caused by thermal gradients and the distribution of these gradients.

Typical bar mat and wire fabric reinforcement practices indicate that heat pipes or other types of structural quality heating elements can be integrated into the slab reinforcement and thereby eleminate part or all of the reinforcing steel. Both the anticipated range of pipe diameters and spacing of in-pavement heating elements are compatible with the size and spacing of steel reinforcement indicating geometric feasibility of the heating system to serve as reinforcement. For a wire fabric continuous reinforced concrete pavement, the heat pipe might be placed above the fabric. To illustrate some of these aspects consider the steel requirements of a slab 9 inches thick of length 40 feet and 12 feet wide.

Longitudinal steel must be sufficient to resist the forces of friction set up when the slab contracts because of a fall in temperature. The amount of steel necessary to hold any crack together is calculated by balancing forces along the horizontal direction. The required cross-sectional area of steel in square inches per foot of width of pavement is

$$A_s = \frac{w\,L\,F}{2\,f_s} = \frac{112.5\ (40)\ 1.5}{2\ (22000)} = 0.154\ \text{in}^2/\text{ft} \qquad \text{(V-8)}$$

where w = weight of slab in lbs. per square foot = 112.5 p.s.f.

L = length of slab

F = coefficient of subgrade friction (generally used value is 1.5)

f_s = working stress in steel (22,000 psi - AASHO structural grade with factor of safety of 1.5)

Using 1/2 inch bars the spacing would be

$$S = \frac{0.196}{0.154} = 1.27\ \text{ft} = 15.3\ \text{inches.}$$

Transverse steel should prevent any longitudinal crack from opening. A conservative design assumes the slab anchored against lateral movement at the longitudinal joint 12 feet from the side. Thus, the area of steel needed is

$$A_s = \frac{w\,L\,F}{2_{f_s}} = \frac{112.5\ (12)\ (1.5)}{2\ (22000)} = 0.046\ \text{in}^2/\text{ft.} \qquad \text{(V-9)}$$

Assuming 3/8 inch bars, the spacing S is

$$S \doteq \frac{0.11}{0.046} = 2.4 \text{ ft} = 28.8 \text{ in.}$$

Heat Pipe Bar Mat - For a basis of comparison consider a heat pipe bar mat consisting of hollow steel tubes (AASHO structural grade) having 1/4" OD and 1/8" ID with a cross-sectional area of 0.0367 square inch. Using the above required values of area of steel for the longitudinal and transverse directions, one obtains for the heat pipe spacing

$$\text{longitudinal spacing} = \frac{0.0367}{0.154} = 0.238 \text{ ft} = 2.86 \text{ in}$$

and

$$\text{transverse spacing} = \frac{0.0367}{0.046} = 0.8 \text{ ft} = 9.6 \text{ in.}$$

The above spacing requirements are compatible with the thermal requirements needed for melting in association with the thermal conductivity of concrete as well as the depth of concrete cover above the mat. With the mat located 1.5 inches below the slab surface, the heat pipe system can deliver to the surface the required thermal power with a longitudinal spacing of 2.86 inches.

5. Temperature Gradient Effects

Thermal gradients across the slab cause warping stresses. Consider the above 9-inch thick slab supported on a subgrade with a modulus of 100 pci and subject to a winter month temperature differential of $3^{o}F$ per inch of slab. For a poisson's ratio of 0.15 and a elastic modulus of 4×10^{6} psi, the radius of relative stiffness is 39.71 inches. With a coefficient of thermal volume change of 5×10^{-6} in/in^{o}F, the warping stress is

$$\sigma = \frac{E \epsilon_t \Delta t}{2} \left[\frac{C_1 + \mu C_2}{1 - \mu^2} \right] = 376 \text{ psi} \qquad \text{(V-10)}$$

where $C_1 = 1.02$ and $C_2 = 0.4$ and are the Bradbury warping coefficients. Such warping stresses may be a high percentage of the ultimate tensile strength of the concrete and when coupled with wheel loading stresses might cause failure of the slab. This combination of warping and load stresses depends on the position of the externally applied loads and the time of day. During early morning hours, the slab is cooler at the top with the corners warped upward. External loads at the corner, at this time of the day, will result in load stresses that subtract from the warping stresses.

The above treats a uniform temperature gradient. It is recommended that the effects of local temperature gradients including non-linear variations be studied with special emphasis on any deterioration of the pavement slabs.

6. Construction Practices

There are a number of construction practices that have important effects on a deicing system. Care and common sense in construction are necessary for a successful installation.

Side forms used in construction of concrete pavements act as forms to hold the concrete in place during the hardening process, provide a straight-edge to work against in hand-finishing, and they act as rails to carry the pavement finishing mechanical equipment. In a possible conceptual design of a heating system, the transporter pipes enter the concrete pavement through the sides of the slab and run transversely across the slab approximately 1.5

or 2 inches from the top. This means that they must pass thru the side forms near the top with a spacing ranging from 1 to 2 feet. Some modification of side forms would be necessary with perhaps a simple latch to bridge each heat pipe hole. This would require some additional labor for setup as well as labor and care in removal of side forms.

With the heat pipes entering the side of the concrete pavement and concrete trucks delivering batches of concrete to the paving spreaders or paving mixers, care is required to prevent distorting the pipe system. In addition, construction of highway shoulders would become somewhat more difficult because of the care necessary to prevent damage to the heat pipes running thru the shoulder areas.

To assist in consolidation of the concrete in the slab forms, some finishing machinery is equipped with a tamping bar system as well as vibrating tubes immersed in the concrete. Care would need to be exercised to insure that the horizontal heat pipe system located near the slab surface is not damaged or displaced.

The formation of transverse contraction or expansion joints may be done using a self-propelled saw with commercial diamond saw blades. Care must be taken to insure that the heat pipe system is not damaged during this process.

Drainage systems such as under-drains, side-drains, ditches, filters, etc., must be planned and constructed so as not to interfere with the heat pipe system.

G. Fission Product Capsules

The fission product encapsulation model employed as a reference in this study was provided by the General Electric reprocessing plant at Morris, Illinois.

The capsule is 13 feet long, 6 inches in diameter, having a volume of 2-cubic feet. With fission products aged 5 years, the net heat inventory is 1.5 KW per capsule which corresponds to 5100 BTU. Three year old fission products would have a 5 KW per capsule activity; however, the decay rate is high for the newer fuel. It would decay to 55% in one year. To avoid the need to add more capsules at frequent intervals, the aged fuel is preferred. Shielded containers for the fuel capsules must be designed to accept additional capsules, which means sizing the container accordingly and incorporating a means of access to the container.

H. Determination of Electrical Energy Costs

1. Rate Structure

Rates are considered which are the best available commercial rates for a typical utility company in the Maryland area. There is, at present, no provision by which highway deicing could obtain a preferential rate such as is afforded to street lighting. It is likely that, should deicing become prevalent by electrical means, this matter would be reviewed by the Utilities Commission.

Electricity is sold in two modes, each of which has a different cost structure. In Mode A, the utility company provides a transformer that supplies a stepped-down voltage from the high tension transmission line. In Mode B, the utility company provides high voltage service and the customer provides his own transformer.

In either mode, power costs have a two-part composition--one related to the peak power demand; the other to the integrated power consumption. Typical rates are as follows for the two modes:

Mode A

The power company provides power at 480, 380, etc., volts as required.

Demand Cost - The demand cost is charged on a monthly basis, integrating each 1/2 hour.

KW	Cost per KW
up to 60	no charge
up to 440	$1.92
over 500	$1.80

Utilization Block Costs

KWH	Cost per KWH
550	5.21¢
2,650	3.30¢
6,800	2.25¢
15,000	1.48¢
75,000	1.19¢

Note: The above summarizes the first 100,000 KWH; the next 175,000 KWH costs 1.04¢/KWH.

Mode B

The power company provides voltage of 4160, 13,000, or 33,000. (Most probably 13,000 volts will be supplied.)

Demand Cost (Monthly Charge)

For 200 KW or less - $340

For the next 1,800 KW - $1.69/KW

For larger blocks - the rate is progressively reduced.

Utilization Block Costs

KWH	Cost per KWH
up to 50,000	1.11¢
50,000 to 250,000	0.98¢

2. Evaluation of Storage Mode

If storage is employed, the peak demand is much lower than for an on-the-line system, although more total power is needed because of inefficiencies of recovery of stored power. A calculation was made for a typical installation model to evaluate relative costs. The storage mode is more expensive to operate, based on power costs alone.

Demand System, No Storage (assumes 5 months deicing)

484 MWH total; 672 KW maximum demand rate.

Mode A

The power company provides transformer and substation. Net cost is 19¢ per square foot of highway.

Mode B

The power company provides high voltage and the customer supplies transformer. (Cost of transformer not included.) Net cost is 15½¢ per square foot of highway.

Storage System (assumes 50% recovery and 12 months storage)

968 MWH total; 112 KW maximum demand rate.

Mode A

The power company provides transformer and substation. Net cost is 24½¢ per square foot of highway.

Mode B

The power company provides high voltage and the customer supplies transformer. (Cost of transformer not included.) Net cost is 20¢ per square foot of highway.

I. Ice Sensing Devices

1. Typical Existing Instrumentation

Various devices are applicable to the highway deicing installation. Some are described below:

Sheet and Ice Detector - This unit is manufactured by Hygrodynamics, Inc., of Silver Spring, Maryland. It has been applied on the DEW line to detect icing on towers, antennas, etc.; and it has been used in Washington, D. C., to control a heated pedestrian ramp over a highway. Generally, it is mounted on a pole above ground. It reacts before ice forms when conditions are favorable (moisture/temperature).

Kar Trol Ice, Snow, and Frost Detector - This unit was designed by Signal Co., Inc., Houston, Texas. This unit activated "Ice-On-Roadway" signs on an Amarillo overpass. It has a moisture sensing element that mounts flush with the pavement. The temperature element is buried in the slab surface.

Snow Detector - This unit is produced by Rails Company, manufacturers of railroad signal and maintenance equipment. It detects snow, freezing rain, hail, ice, and drifting snow. The control device actuates gas or electric heaters; after a preset time cycle, the heaters are deactivated if the snow conditions have been eliminated.

Road Research Laboratory System - The Road Research Laboratory of Great Britain developed an automatic control system, patented May 23, 1961. The control system is regulated by a moisture detector and a temperature thermostat. The moisture detector has two electrodes that are embedded in the road surface. These electrodes measure the insulation resistance between them. A water film causes a drop in resistance and a response from the unit. There is a separate detector pad equipped with a heater to detect frost or dry snow. Either is melted to actuate the moisture detector.

2. Evaluation

In all cases, the present instrumentation is planned to produce an electrical control signal. This signal is suitable for turning systems on or off. In the case of heat pipes, this type of signal could be utilized to actuate a solenoid valve; however, this would entail running control wires to each unit and therefore introduce the need for electrical power in an otherwise non-electrical system.

Some consideration was given during this study to determine methods of thermal control, which could be applied to heat pipes, that would be more in keeping with the passive nature of the system. There are two methods that appear to offer possibilities for further development. One requires a heat pipe fluid with characteristics that produce auto-regulation in response to the temperature of the roadbed. The other has a detector unit which responds to the temperature of incipient ice formation on the road and, by mechanical action, operates a valve inside the heat pipe. It appears that a passive solution to the heat pipe icing detector is feasible. For non-heat pipe systems commercial icing detectors are available. An objection to these devices was expressed by the Pennsylvania Highway Department. Their objection was related to their intended application, which was the control of illuminated caution signs that would warn the motorist of icing on bridges. There are many factors that influence the appearance of icing on the roadbed. For example, the traffic lanes of a four-lane roadway might be clear of ice because of the mechanical effects produced by moving vehicles, whereas the less traveled passing lanes might be covered with ice. Two bridges in the same vicinity can see essentially identical conditions as would be detected by instrumentation, whereas only one might have icing at a particular time. The net result of these idiosyncrasies is that there is very often a discrepancy between the warning sign and the actual condition. This results in a tendency for the motorist to ignore the warning signs, thus reducing their effectiveness.

The instrumentation problem is different for a deicing system than it is for warning signal system. The deicing system can overrespond by a certain amount. The cost of overresponse can be evaluated for the particular installation and adjusted accordingly.

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